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AFML-TR-79-4019

IMPACT DAMAGE ON TITANIUM LEADING EDGES FROM SMALL SOFT-BODY OBJECTS

Robert S. Bertke
John P. Barber

University of Dayton Research Institute
300 College Park Avenue
Dayton, Ohio 45469

February 1979

Interim Technical Report
For Period April 1976 - August 1977

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AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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THEODORE NICHOLAS, AFML/LLN
Project Engineer

NATHAN G. TUPPER, Chief
Metals Behavior Branch
Metals and Ceramics Division

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Impact damage on titanium leading edge configurations was investigated by performing leading edge soft-body impacts on flat-edge and tapered-edge specimens. The objectives were to determine the laboratory specimen size, boundary condition, and test methods necessary to adequately simulate the leading edge local damage of actual blades from soft-body impacts (such as birds). The effects of leading edge geometry, specimen mounting, impact velocity, impactor type, impactor size, and impact angle were investigated. The damage modes excited in titanium were identified. Damage measurement techniques were devised and the

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20. ABSTRACT (cont'd)

and the damage quantified. Comparisons of the damage were drawn regarding the effects of specimen size and mounting.

PREFACE

The effort reported herein was conducted by the Dynamic Mechanics Group of the University of Dayton Research Institute, Dayton, Ohio, under Contract F33615-76-C-5124, for the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio. Air Force administrative direction and technical support was provided by Dr. Theodore Nicholas, AFML/LLN.

The work described herein was conducted in the AFML Impact Mechanics Facility of The Air Force Materials Laboratory at Wright-Patterson Air Force Base during the period from April 1 76 to August 1977. The principal investigator was Mr. Robert S. Bertke of the University of Dayton Research Institute. Project supervision and technical assistance was provided by Dr. John P. Barber of the University of Dayton Research Institute.

The authors wish to acknowledge the following persons of the University of Dayton Research Institute who provided direct support to this work. Mr. Charles E. Acton conducted the impact testing, Mr. Richard Tocci conducted the photographic coverage, and Mrs. Sue C. Gainor conducted the typing of this manuscript.

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INTRODUCTION

Modern gas turbine engines for aircraft utilize fan blades made from homogeneous metals. Advanced engine concepts currently under development envision using fan blades made from intermetallic and nonmetallic composite materials. An important property of fan blade materials is the resistance of the material to impacts from birds, stones, ice balls, and other items. The damage inflicted by such impacts is known as foreign object damage (FOD).

Impacts on fan blades can be classified either as hard-body or soft-body impacts. The phenomena associated with hard objects (such as munitions) and soft objects (such as birds) are fundamentally different. Hard objects tend to retain their size and shape during the impact process. This results in intense localized damage at the impact site with relatively slight effects at larger distances. Soft projectiles deform grossly upon impact and produce less localized damage but significantly greater effects at large distances from the impact site. The damage at greater distances from the impact site is largely due to the total impulse transferred to the blade during the impact.

The FOD problem of fan blade materials can be divided into two separate problem areas. One concerns the local blade damage and the second deals with the structural damage. Local damage occurs during the impact and is confined to within one or two projectile diameters of center of the impact site. Structural damage occurs at later times and at points which are, in general, well away from the impact site.

This paper describes an experimental study conducted to investigate the local damage problem. A photograph of typical birdstrike local damage on the leading edge of a titanium fan blade is shown in Figure 1. The blade was obtained from an operational aircraft and was removed when post-flight inspection revealed that the engine had ingested a bird during flight. The leading edge was curled back (material rolled back and under) and cracked.

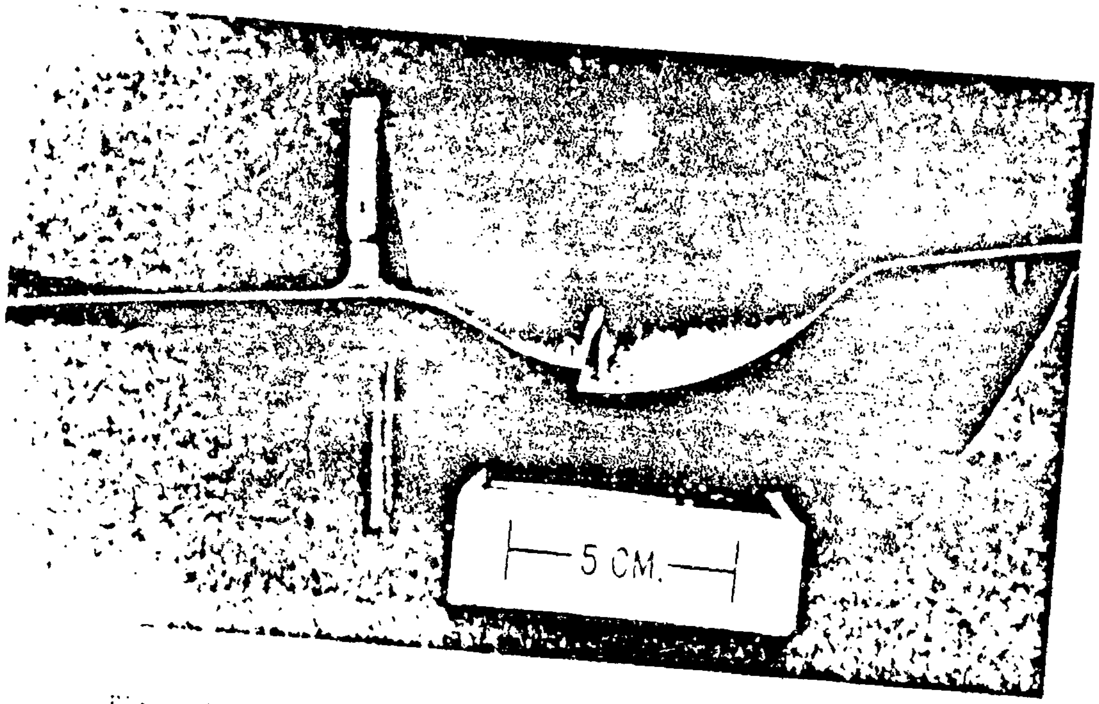


Figure [illegible]. [illegible] damage of actual fan blade from birdstrike.

SECTION II

EXPERIMENTAL PROGRAM

The experimental program involved non-rotating impact tests on small test specimens of blade materials. A soft (bird-like) material was gun launched and impacted the edge of the test specimens. This method of testing provided consistent and precise control of the impact parameters. The important impact parameters include the impact velocity, the angle of impact, the projectile type and mass, the target material, and the target thickness and geometry.

2.1 STUDY OBJECTIVES AND APPROACH

The overall objectives of the study were to determine the laboratory specimen size, boundary conditions, and test methods necessary to adequately simulate the leading edge local damage of actual blades from soft-body impacts (such as birds). The study was limited to soft-body impacts since bird ingestion into engines results in the highest frequency on major fan blade damage. During the landing and takeoff phases of flight, the bird-strike probability is greatest and the ingestion conditions are most severe[1].

The study was divided into two phases of experimental work. The first phase of experiments was directed toward developing a laboratory method of generating damage similar to that received on actual blades from a soft-body impact on laboratory size specimens. In this phase, the damage modes excited in titanium were identified and a damage measurement technique was developed to characterize the damage modes and permit proper consistent damage measurements.

The second phase of experiments was directed toward investigating the effects of specimen size, leading-edge geometry, specimen mounting, impact velocity, impact angle on impact damage. Two different densities of impactor material were employed.

The approach chosen to develop the laboratory methods of evaluating the local damage characteristics of fan blade materials involved the following steps

1) Define the impact conditions of interest (impact angle, impact velocity, soft-body type and size);

2) Establish laboratory techniques to simulate leading edge damage of actual blades on laboratory size specimens at defined impact conditions;

3) Conduct specimen impact tests on titanium specimens of various sizes and using various mounting methods;

4) Identify damage modes;

5) Establish techniques to make proper damage measurements;

6) Measure specimen damage;

7) Compare damage for various size specimens and boundary conditions;

8) Select proper specimen size, boundary condition, projectile type, and projectile sizes for further impact testing;

9) Conduct specimen impact tests varying important projectile, impact, and blade geometry parameters.

2.2 ANTICIPATED DAMAGE MODES

The anticipated local damage modes of metal (such as titanium) blades are shown in Figures 1 and 2, and include; (1) plastic deformation, (2) cracking, (3) curl-back, (4) mass loss. Measurements designed to characterize the plastic deformation include the plastically deformed area (A_1), the frontal area (A_2) (looking edge-wise at the specimen), and the maximum plastic deformation. Cracking is characterized by the number of cracks, their location with respect to the impact point center, their length, and a sketch of their directions. Curl-back is characterized by measuring the area of plastic deformation, the frontal area looking edge-wise onto the specimen, and a sketch to record its shape and dimensions.

2.3 TEST MATRIX

The objective of the first phase of experiments was to generate local damage on test specimens similar to that which would occur on actual blades at conditions typical of an in-flight bird impact. In addition, the damage modes of 6Al-4V titanium specimens were to be identified and a technique developed to characterize the damage. In this series of testing, the projectile material utilized was a hardened silicone rubber (RTV-560), a common substitute bird material. The impacts were slicing edge impacts at angles of incidence of 30 degrees or 90 degrees. The impact velocity ranged from approximately 60 to 600 m/s, the range of velocities of interest in bird-strikes on fan blades.

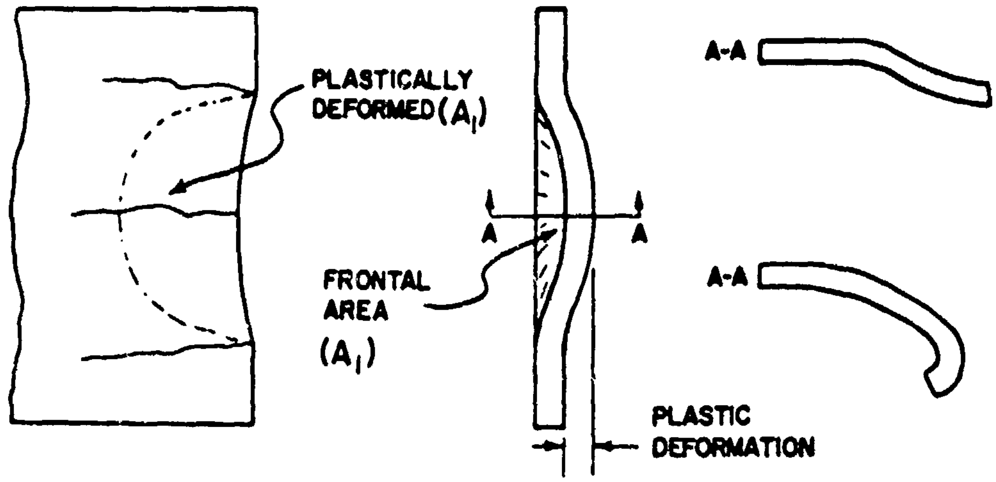


Figure 2. Local damage modes for titanium.

In the second phase of testing, the effects of specimen size, leading edge geometry, and mounting methods were investigated utilizing two densitites of microballoon gelatin, another common bird substitute, as the projectile material. Again, the impacts were slicing edge impacts at an angle of incidence of either 15 or 30 degrees and the impact velocities ranged from approximately 100 to 500 m/s.

2.4 EXPERIMENTAL SET-UP

A schematic of the range set-up used for studying the local damage problem for the Phase 1 testing is shown in Figure 3. It consisted of a launch tube, a sabot catch tank, a velocity measuring system, a ballistic pendulum, a high speed framing camera, and a ballistic felt backstop. In the Phase 2 testing the set-up remained basically the same except that the ballistic pendulum and high speed camera were not utilized.

2.4.1 Launch Tube

The launch tube had a smooth bore of 4.26 cm and a length of 1.83 m. The projectile was fitted into a recessed pocket in a lexan sabot to provide protection and support for the projectile during launch. The projectile/sabot package was launched down the tube by utilizing powder gas. A sabot deflector[2] was located at the muzzle of the launch tube. This deflector slowed down the sabot, permitting the projectile to separate and continue on trajectory towards the target specimen. After separation of the projectile from the sabot, the device diverted the sabot at an angle of a few degrees to the trajectory. The projectile passed through a 4.50 cm hole in the sabot catch tank backplate and struck the target. The deflected sabot struck the backplate of the catch tank.

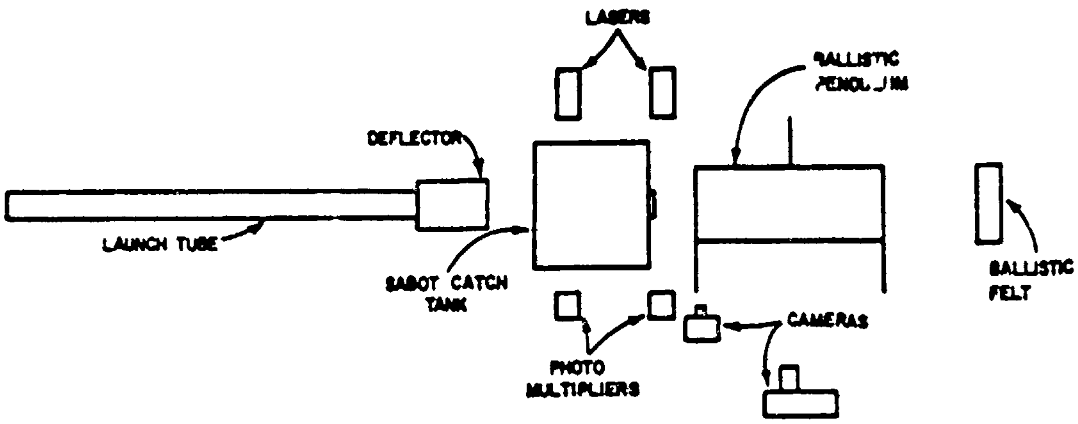


Figure 3. Schematic of range set-up for studying local damage problem.

2.4.2 Velocity Measurements

The projectile velocity was measured by utilizing a pair of HeNe laser/photomultiplier stations spaced a known distance apart. Each laser projects a beam that intersects the projectile trajectory normal to trajectory and illuminates one of the photomultiplier stations. When the projectile interrupts the first beam, the first photomultiplier station generates a voltage pulse to start a counter-timer. The counter-timer is stopped when the projectile interrupts the second beam. The projectile velocity is then calculated from the travel time between the stations.

2.4.3 Projectile Material and Sizes

For the Phase 1 testing, the projectiles were either 1.78 or 2.54 cm diameter spheres of RTV-560. A typical sphere is shown in Figure 4. The spheres were molded and cured according to the specifications of the manufacturer. The mass of the projectiles was approximately 2 g for the 1.78 cm diameter sphere and 6 g for the 2.54 cm diameter sphere.

For the Phase 2 testing, two densities of microballoon gelatin were utilized and molded 1.27, 1.78, 2.54, and 3.18 cm diameter spheres. The mixture of 40 percent microballoons in gelatin projectile material had a density of about 0.69 g/cm^3 whereas the mixture of 15 percent microballoon in gelatin has a density of about 0.90 g/cm^3.

2.4.4 Target Specimen Size and Mounting Method

The target specimen size for the Phase 1 testing was 7.62 x 22.86 cm with a 3.81 cm length of each end clamped within mounting fixtures

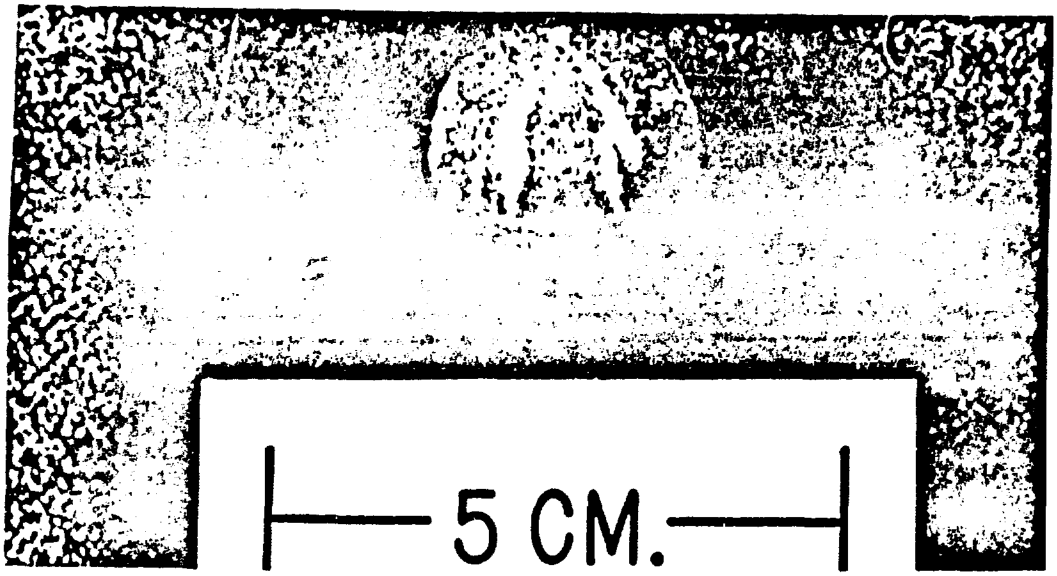


Figure 4. Typical RTV-560 sphere projectile.

as shown in Figure 5. This fixed-fixed mounting technique permitted an overall target size of 7.62 x 15.24 cm between the mounting fixtures. This mounting technique was chosen to minimize any structural damage effects since the study was concerned only with local damage. The mounting fixtures were rigidly fixed at the center of the ballistic pendulum at the desired impact angle.

For the Phase 2 testing, three specimen sizes were investigated. The specimen sizes were 7.62 x 22.86 cm, 7.62 x 31.75 cm, and 10.16 x 38.10 cm. Also tests were conducted utilizing three methods of mounting (fixed-fixed, cantilevered, and free-free). The fixed-fixed method of mounting was accomplished by clamping a 3.81 cm of each end of the specimen within mounting fixtures. The mounting fixtures were in turn rigidly mounted to a heavy beam. The cantilever method of mounting was conducted by clamping 3.81 cm of one end of the specimen with the mounting fixture. The free-free method of mounting was accomplished by taping the specimen to the mounting fixtures. Upon impact, the free-free mounting method permitted the specimen to free flight.

Two specimen thicknesses and two leading-edge thicknesses were utilized in the Phase 2 work. The specimen thickness was either a nominal

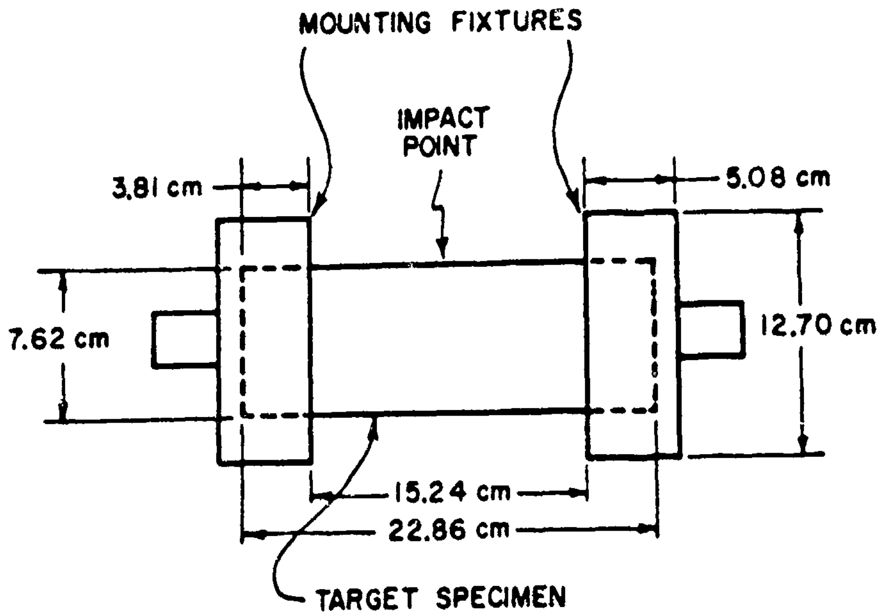


Figure 5. Sketch of test specimen in mounting fixtures.

0.16 or 0.32 cm. The leading-edge thickness was either 0.051 or 0.102 cm. The leading-edge taper for all tapered specimens was four degrees.

2.4.5 Target Alignment

For both phases of testing, target alignment within the mounting fixtures was achieved by projecting a laser beam through the bore of the launch tube onto the target. Since all impacts were edge impacts, the target was positioned such that the laser beam was split by the target edge at the desired impact location of the target. Thus, half of the launched sphere would impact the target (impact portion) and the other half (non-impact portion) would travel past the target edge.

2.4.6 Ballistic Pendulum

A ballistic pendulum containing the target specimen was utilized only in Phase 1 work. It was employed to measure the momentum transfer to the target due to the impact. The pendulum (shown in Figure 6) was constructed as a framework using 2.54 x 2.54 x 0.32 cm channel iron. The mass of the pendulum with the mounting fixtures was 10.686 kg which allowed a peak to peak oscillation amplitude of several centimeters when the target received the minimum anticipated impulse. A standard five wire support system [3,4] was chosen for the suspension system.

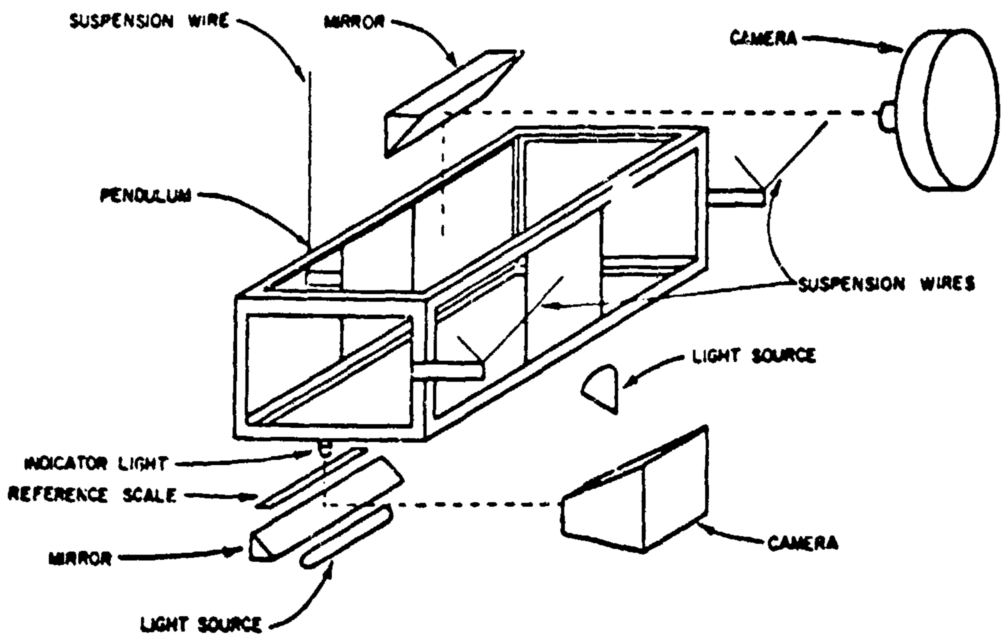


Figure 6. Sketch of ballistic pendulum utilized.

The impulse (P_t) delivered to a pendulum by a ballistic impact is expressed by Equation 1. P_t is expressed in terms of the pendulum mass (M_p). The period of oscillation (T), and the maximum full swing chord length (C) through which the pendulum swings after impact is as follows:

$$P_t = \frac{\pi C M_p}{T} \qquad (1)$$

The technique chosen to provide precise measurement of the pendulum was to rigidly mount a miniature 110 volt glow lamp onto the bottom of the front framework of the pendulum such that its motion could be photographed with an open-shutter camera. The power source for the lamp was 6 volts which barely lights the lamp filament. A reference scale was precisely mounted on a separate mount in the plane of the lamp to provide a displacement and magnification reference on the camera film. The reference scale was photographed prior to impact (using a separate small light source). The indicator lamp was turned on and the camera shutter opened just prior to impact. The shutter was held open during one complete pendulum oscillation. A clear image of the stationary lamp at its initial position prior to impact

together with two others representing the two extreme pendulum positions during the swing were observed. An example is shown in Figure 7. The distance between the two extreme positions is the chord of the pendulum motion (C). The mass of the pendulum with target in position was used in Equation (1) to compute the impulse transferred to the target specimen. The period of the pendulum was measured to be 2.4608 seconds using the technique described by Swift in Reference 4. The pendulum was excited and the period of oscillation was measured by timing the passage through the zero amplitude point with an el ctronic-counter. A pair of fine wires were shorted together by a meta lic element of the pendulum support structure. This triggered the start of the counter. The switch was then removed and not replaced until one-quarter cycle before the counter was to be stopped.

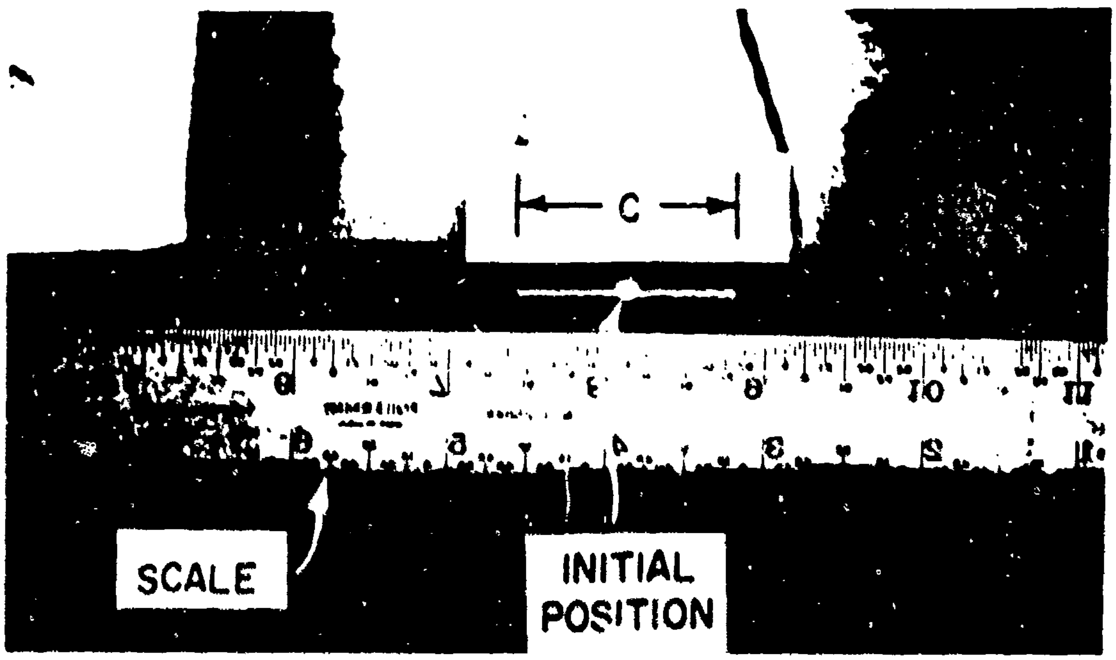


Figure 7. Film record used to measure amplitude of pendulum oscillation.

A calibration check of the pendulum was obtained by impacting and trapping spheres in an enclosed tube mounted in the pendulum. Three calibration shots indicated that the pendulum measured momentum within 3 percent of the calculated momentum projectile.

2.4.7 Dynamic Deformation

The dynamic deformation of the leading edge of a number of selected target specimens in the Phase 1 work was observed edge-on using a system of mirrors and a high-speed framing camera (the framing rate was approximately 20,000 fps). A typical sequence of frames is shown in Figure 8. The target was illuminated with a 10.8 ms duration pulsed light source. Note that the plastic deformation damage is generated in very short times and occurs during the impact event.

2.4.8 Mass Measurement of Projectile Impacting Target

The non-impact portion of the projectile traveling over the target edge was trapped intact in the ballistic felt backstop. The mass of the projectile slice impacting the target was calculated from the initial sphere mass and the trapped non-impact portion mass. Figure 9 shows a photograph of an intact non-impact portion.

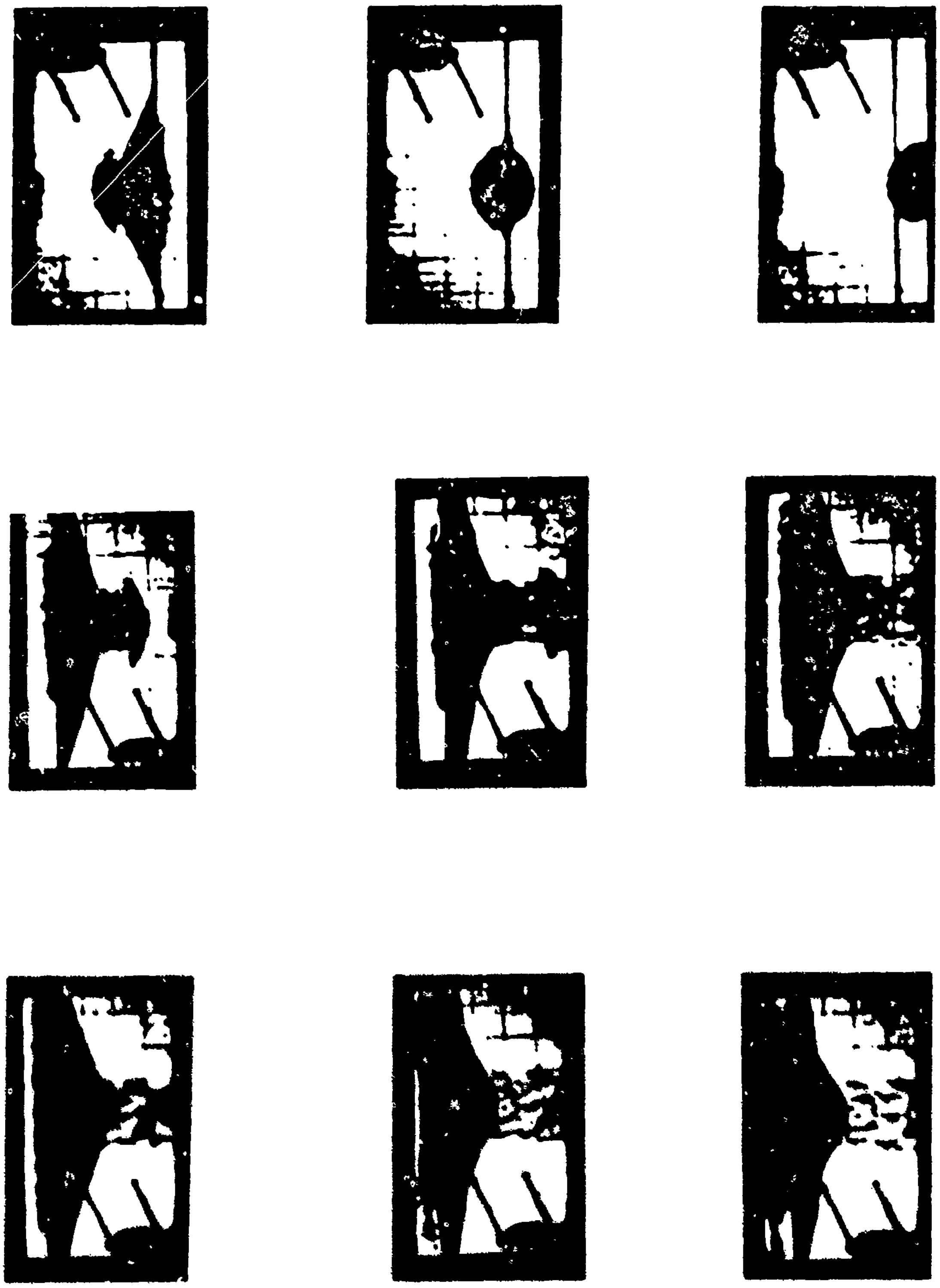
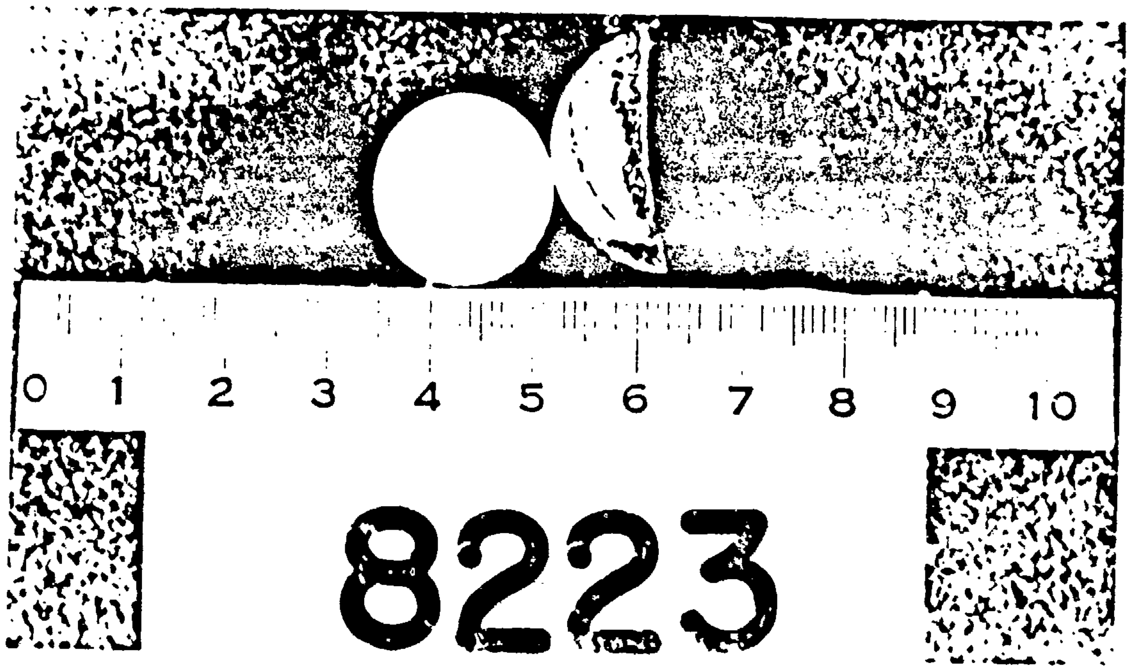


Figure 8. Typical sequence of frames showing impact event.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SECTION III
EXPERIMENTAL RESULTS

The experimental results of both phases (Phase 1 and Phase 2) of work are summarized in the following paragraphs.

3.1 PHASE 1 RESULTS

The initial series of impact tests conducted to identify the damage modes and develop a method of characterizing the damage, was conducted on flat 6Al-4V titanium specimens. The specimens were 7.62 x 22.86 cm with three thicknesses. Five edge impacts were conducted on 0.16 cm thick specimens with 2.54 cm diameter RTV-560 spheres. The velocities ranged from 60 to 600 m/s with an impact angle of 90 degrees. Very little damage resulted. Typical damage received is shown in the photograph of Figure 10. A slight amount of plastic deformation resulted. This damage does not resemble that of an actual blade as shown in Figure 1. These preliminary results indicated that thinner specimens or specimens with a tapered edge were probably necessary to generate damage similar to that received by actual fan blades.

Impact tests on the edge of 0.10 and 0.05 cm thick flat titanium specimens with 2.54 cm diameter RTV spheres were conducted at approximately 450 m/s. Impacts at 90 and 30 degrees resulted in very severe damage. The damage did not bear any resemblance to that of the actual blade as shown in Figure 1. Photographs of typical damage generated on these specimens for 30 degree impact angles are shown in Figures 11 and 12. Notice that tears occurred at the mounting fixtures for both thicknesses and buckling was predominant for the thinner specimen.

The next series of impacts in the Phase 1 testing was conducted on 0.21 cm thick specimens having about a four degree tapered edge and an edge thickness of about 0.04 cm. The projectile velocities for these impacts ranged from 220 to 456 m/s and the impact angle was 30 degrees. Figures 13 through 17 show photographs of the damage generated for edge impacts of 2.54 cm diameter RTV spheres on these specimens. Notice that the damage generated is very similar to that for an actual blade (see Figure 1)

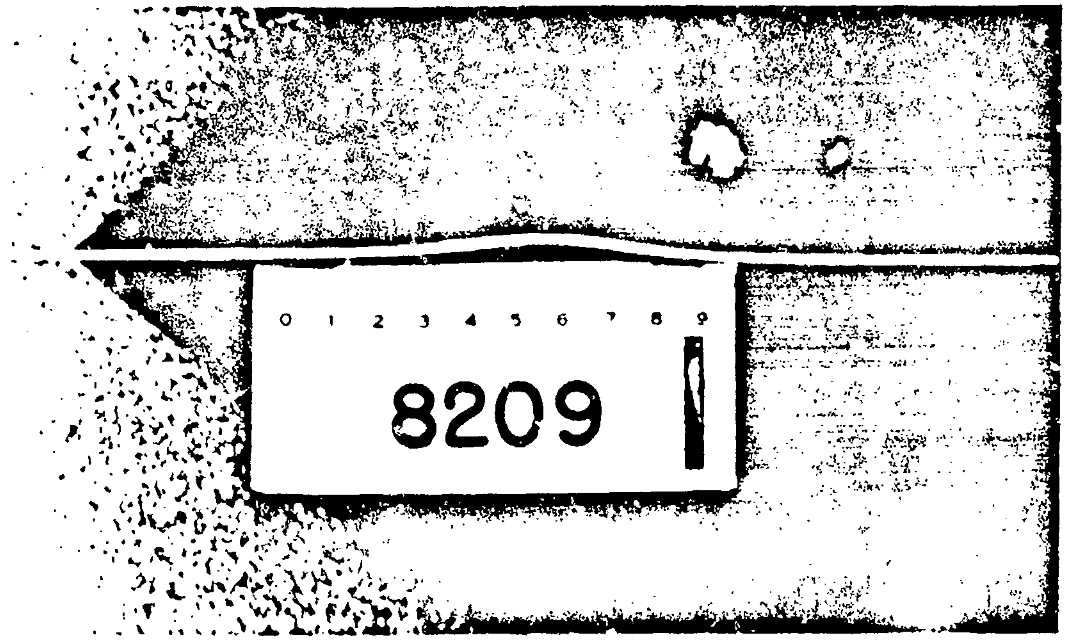

Figure 10. Typical damage received on 0.1[illegible] cm thi[illegible] flat t[illegible] [illegible]imens.

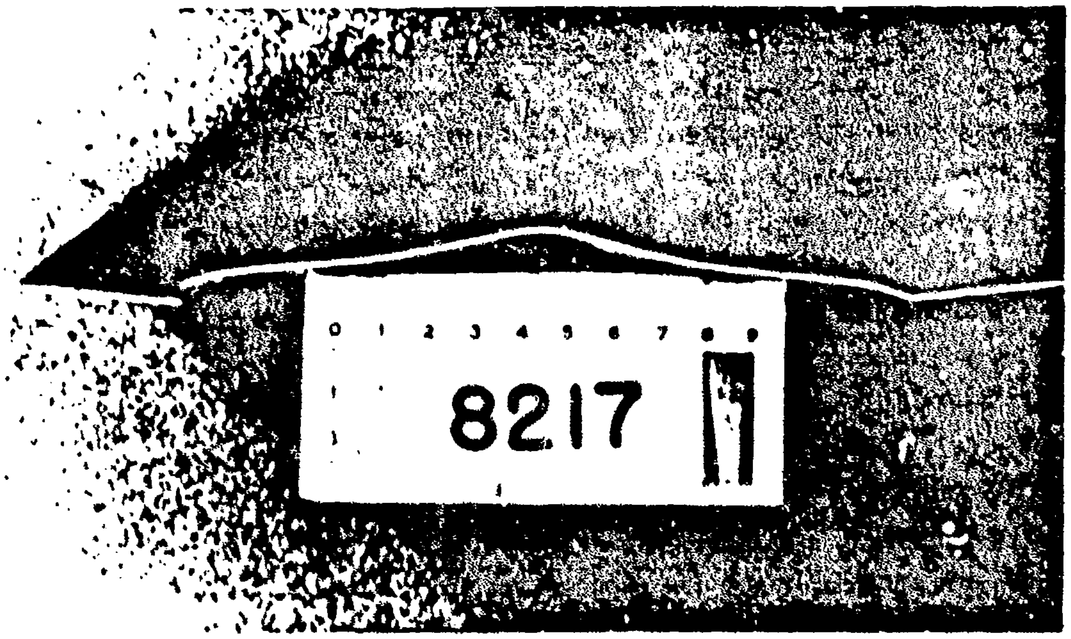

Figure 11. Typical damage received on 0.10 cm thick flat titanium spe[illegible]imens

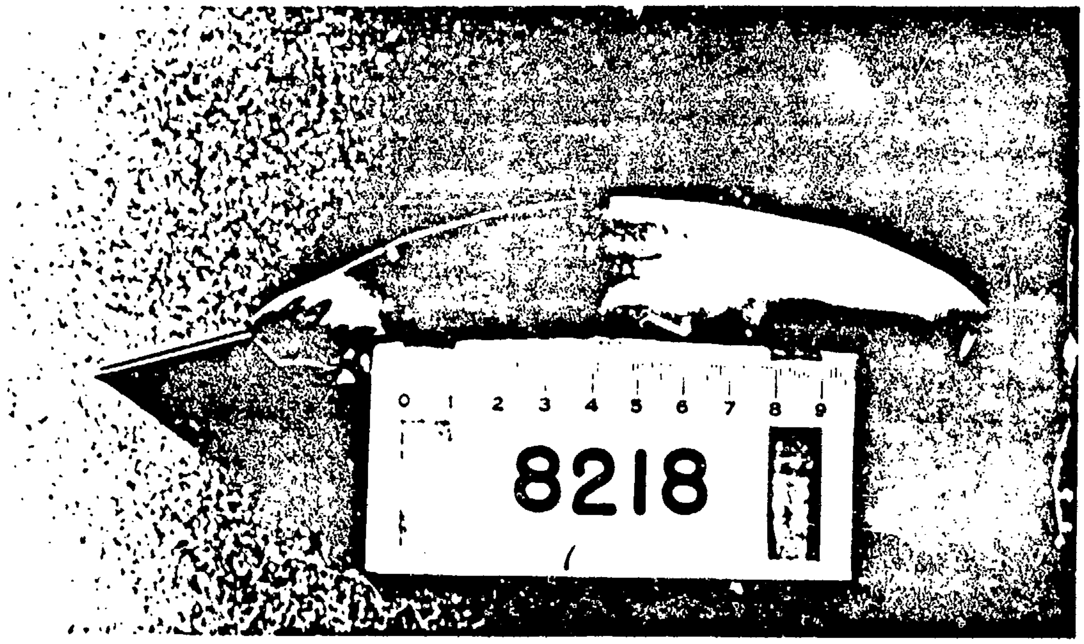

Figure 12. Typical damage received on 0.05 cm thick flat titanium specimens.

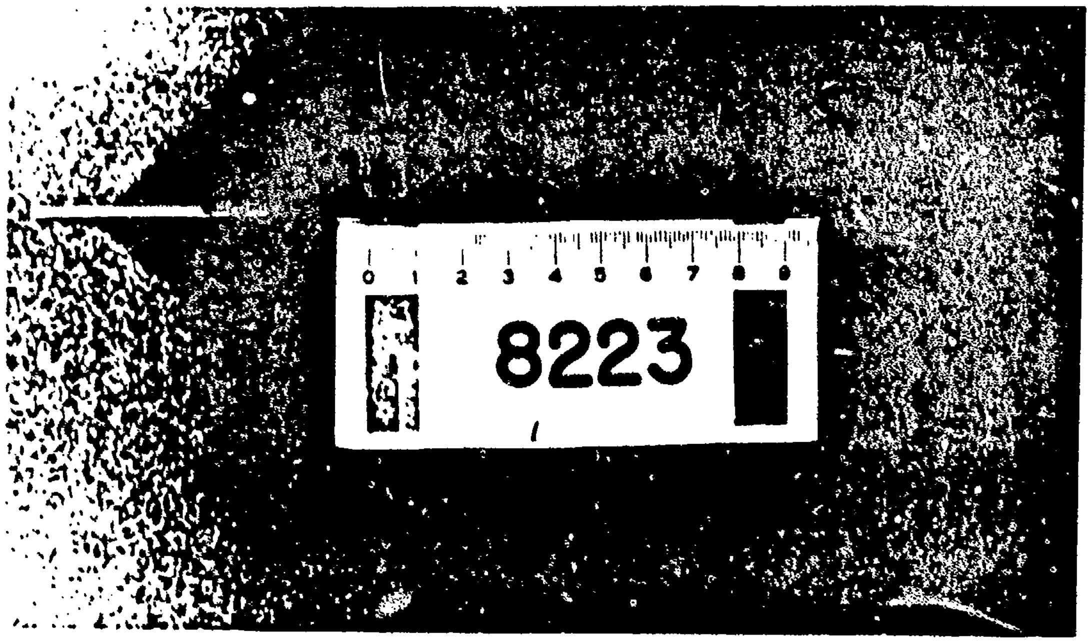

Figure 13. Damage received on tapered-edge titanium specimen at projectile velocity of 220 m/s.

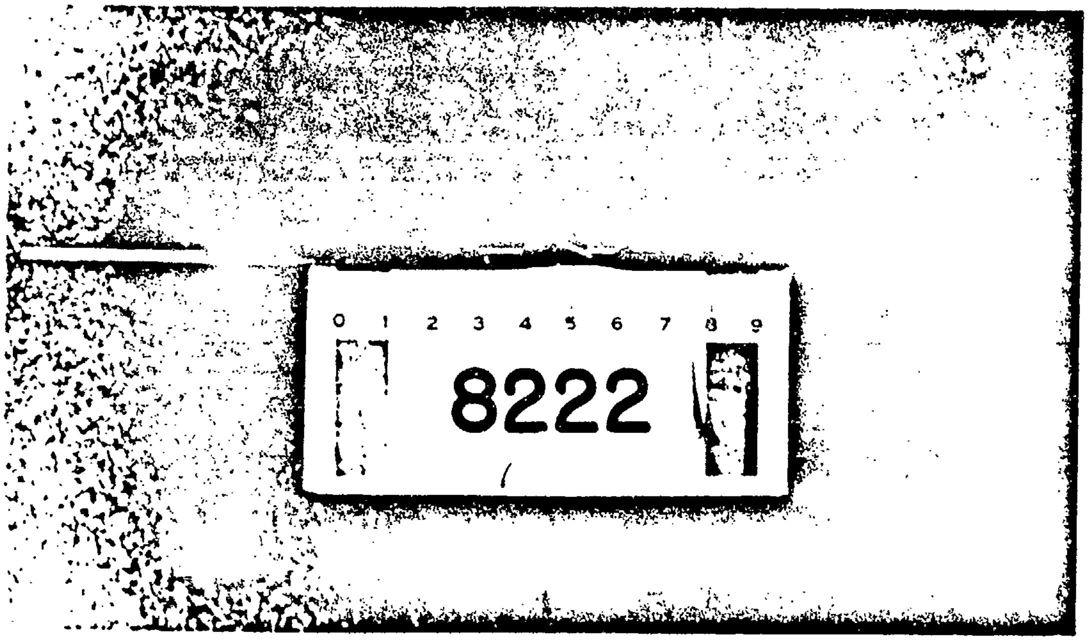

Figure 14. Damage received on tapered-edge titanium specimen at projectile velocity of 310 m/s.

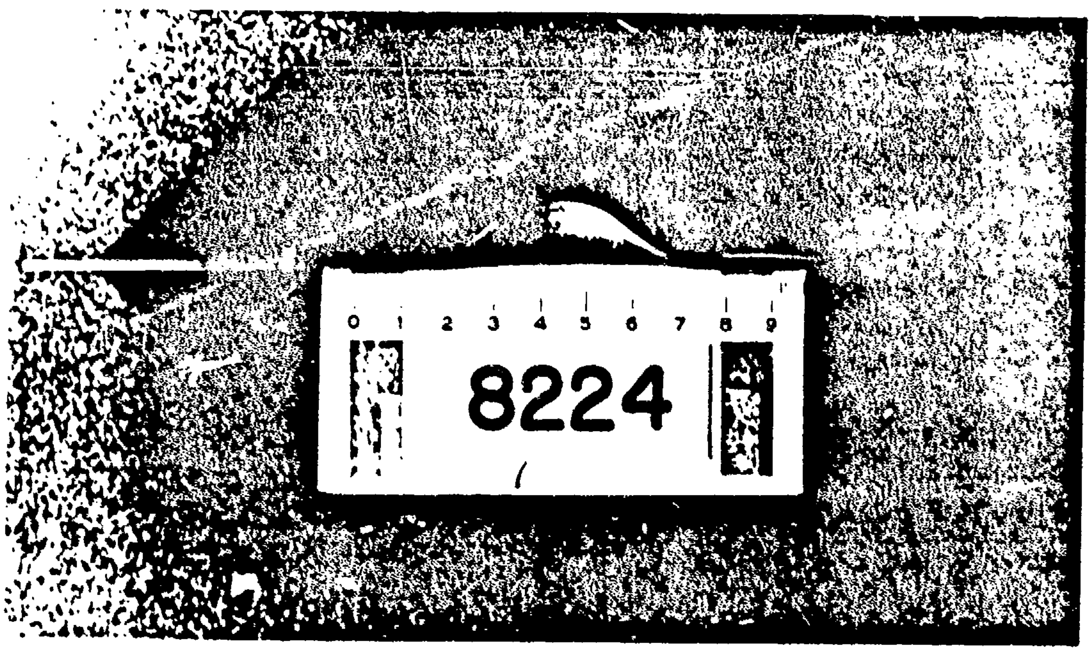

Figure 15. Damage received on tapered-edge titanium specimen at projectile velocity of 360 m/s.

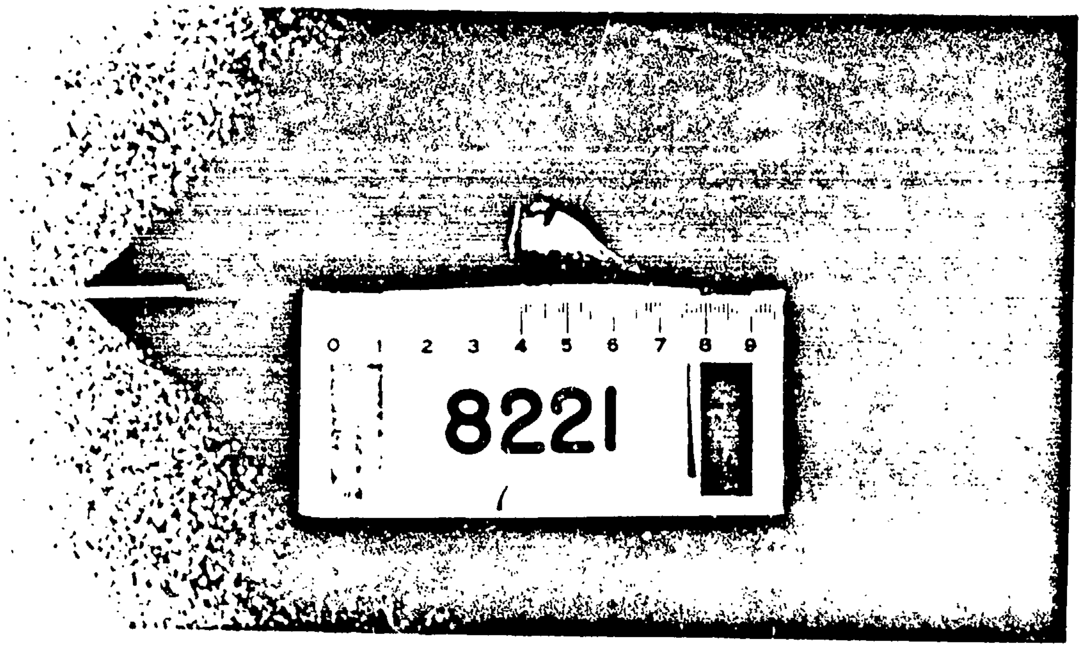

Figure 16. Damage received on tapered-edge titanium specimen at projectile velocity of 418 m/s.

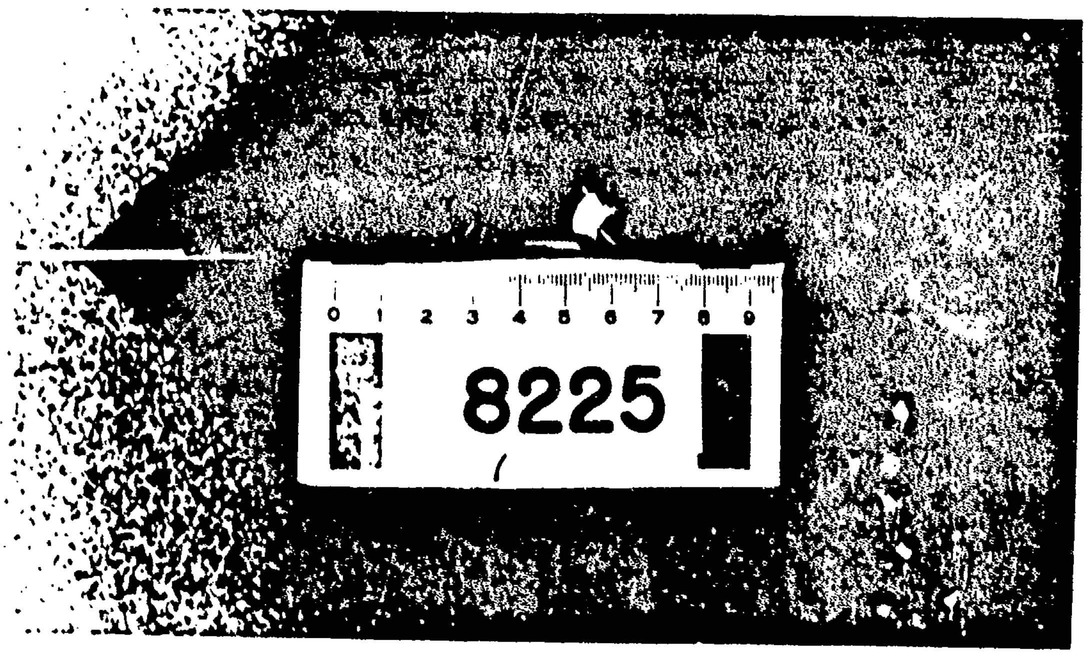

Figure 17. Damage received on tapered-edge titanium specimen at projectile velocity of 456 m/s.

indicating that local damage is very sensitive to blade leading edge geometry. Separate distinct damage modes can be identified in the photographs. Figure 13 (impact velocity of 220 m/s) shows the initiation of plastic deformation. Increasing the velocity to 310 m/s increased the plastic deformation as shown in Figure 14. A further increase of velocity to 360 m/s results in a substantial amount of plastic deformation with the initiation of metal leading edge roll-back or curl-back as shown in Figure 15. Metal cracking and metal roll-back results at a velocity of 418 m/s as shown in Figure 16. Finally roll-back and perforation (metal missing) resulted at a velocity of 456 m/s as shown in Figure 17.

The damage for these impacts was characterized by measuring the momentum transfer to the specimens, the maximum plastic deformation, the plastic deformation area, and the frontal area generated looking at the specimens edge-wise. Crack lengths and locations and specimen mass loss values are also documented.

A similar study of edge impacts on tapered titanium specimens was conducted with 1.78 cm diameter RTV-560 spheres. Results of impacts on the tapered titanium specimens are summarized in Figures 18 and 19. Figure 18 shows a plot of the normalized momentum transfer (measured momentum transfer divided by initial projectile momentum) and the plastic deformation area versus the impact velocity. Notice that the momentum and plastic area increase with increasing velocity until perforation of the specimen occurs. Upon perforation, the momentum and plastic area both decrease in value. Figure 19 shows a plot of the frontal area and maximum deformation versus the impact velocity. The frontal area also increases in value with increasing velocity until perforation occurs. At perforation, the frontal area begins to decrease in value with increasing velocity. Summarizing, the momentum transfer and all area measurements of the damage increase with increasing impact velocity until perforation occurs. Upon perforation, they decrease with increasing velocity.

Data for the Phase 1 impacts are collected in Appendix A.

3.2 PHASE 2 RESULTS

The Phase 2 testing involved conducting leading-edge impacts on flat and tapered-edge specimens with two densities of microballoon gelatin projectiles. The phase 2 testing can be divided into two series of tests.

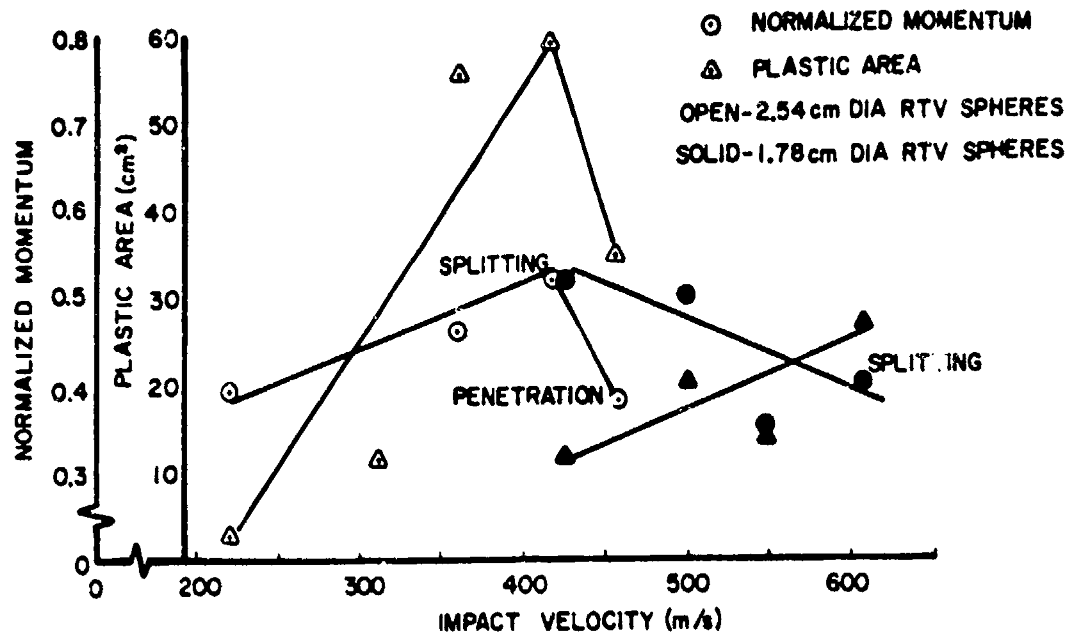

Figure 18. Plot of normalized momentum and plastic deformation area versus impact velocity for tapered-edge specimens.

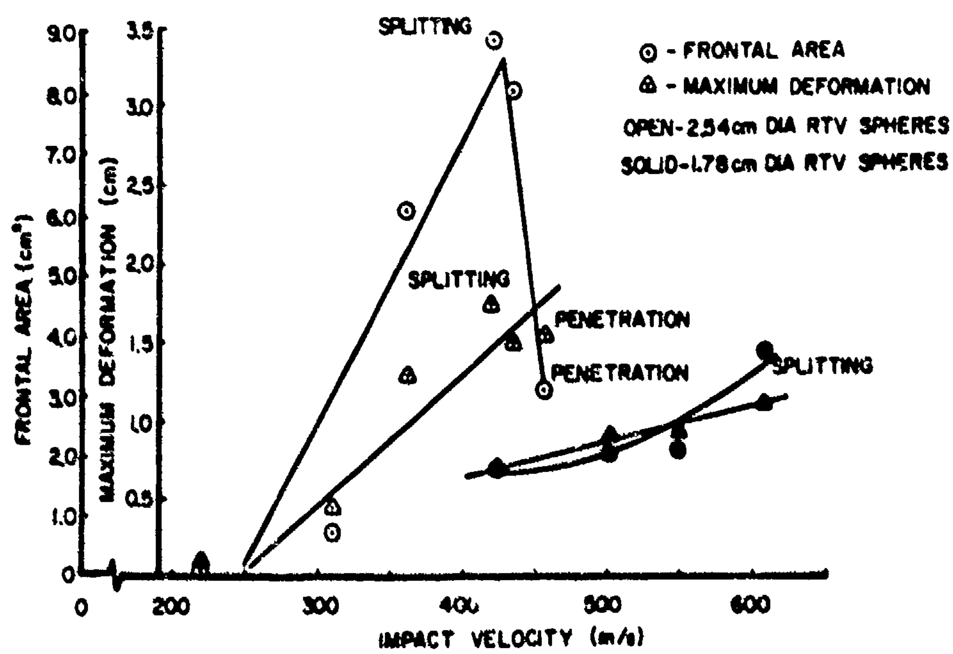

Figure 19. Plot of frontal damage area and maximum deformation versus impact velocity for tapered-edge specimens.

The first series of tests was conducted using a mixture of 40 percent microballoons in gelatin for the projectiles. The measured density for the 40 percent microballoon-gelatin projectiles was 0.69 g/cc. The second series of tests was conducted using a mixture of 15 percent microballoons in gelatin for the projectiles. The density of the 15 percent mixture was measured to be 0.90 g/cc which is the approximate density for chickens. Data from the Phase 2 testing is collected in Appendix B.

3.2.1 40 Percent Microballoon-Gelatin Projectile

The first series of fifteen tests utilized both flat and tapered specimens with the 40 percent mixture of microballoon gelatin projectiles. The size of the flat specimens was 10.16 x 38.10 x 0.16 cm while the tapered-edge specimens were of two different sizes but only one thickness. The tapered leading-edge specimen sizes investigated were 7.62 x 22.86 cm and 10.16 x 38.10 cm with a specimen thickness of 0.16 cm. The leading-edge thickness was 0.051 cm with a taper angle of four degrees.

The first four impacts in this series were conducted on the flat (6Al-4V) titanium specimens mounted either fixed-fixed or cantilevered and impacted at velocities ranging from 140 to 480 m/s. The impacts were leading-edge impacts at an angle of incidence of 30 degrees utilizing 2.54 cm diameter projectiles. For these impacts, the most severe damage was only a slight amount of plastic deformation. The damage on the flat specimens did not bear any resemblance to that of the actual blade as shown in Figure 1.

The remaining eleven impacts in this series were conducted on the four degree tapered leading-edge specimens. Three different mounting techniques were used including the fixed-fixed, cantilever, and free-free methods. For these tests, the impacts were 30 degree leading-edge impacts with 1.78, 2.54, and 3.18 cm spheres of the 40 percent microballoon-gelatin mixture at velocities ranging from 310 to 525 m/s.

Plots of the measured damage versus impact momentum are given in Figures 20 through 22. Figure 20 gives a plot of the measured plastic deformation area damage. Figure 21 gives a plot of the frontal area damage while Figure 22 gives the plot of the maximum leading edge deformation damage.

A summary of the damage results for the tapered specimens is given in Table 1 for the 40 percent microballoon-gelatin projectiles. Impacts at

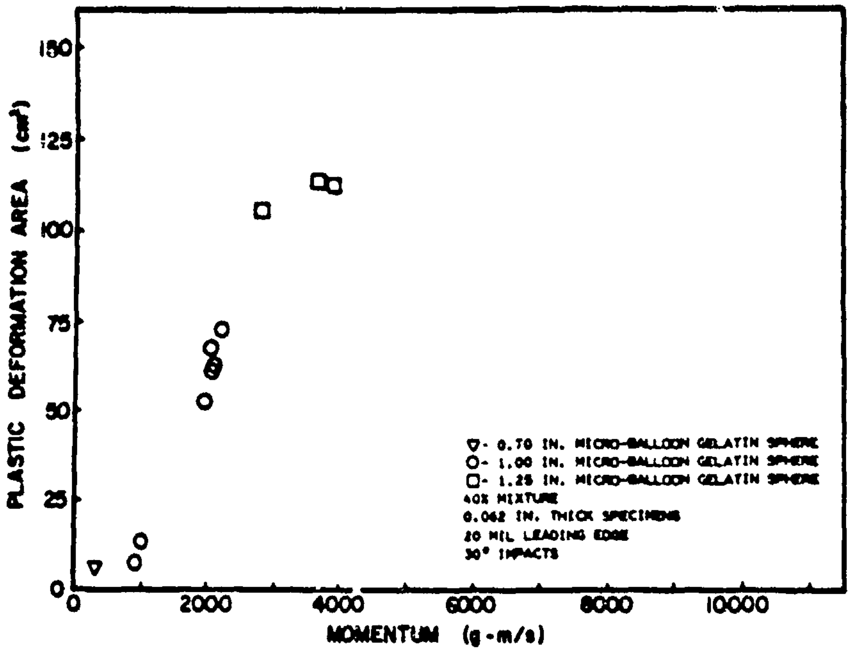

Figure 20. Plot of plastic deformation area versus momentum for 40 percent microballoon gelatin.

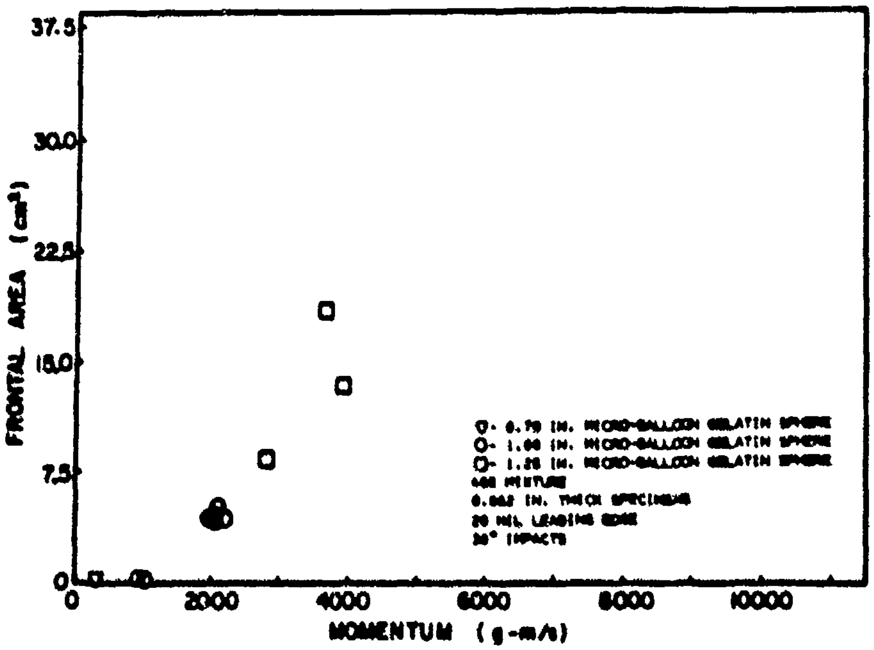

Figure 21. Plot of frontal area versus momentum for 40 percent microballoon gelatin.

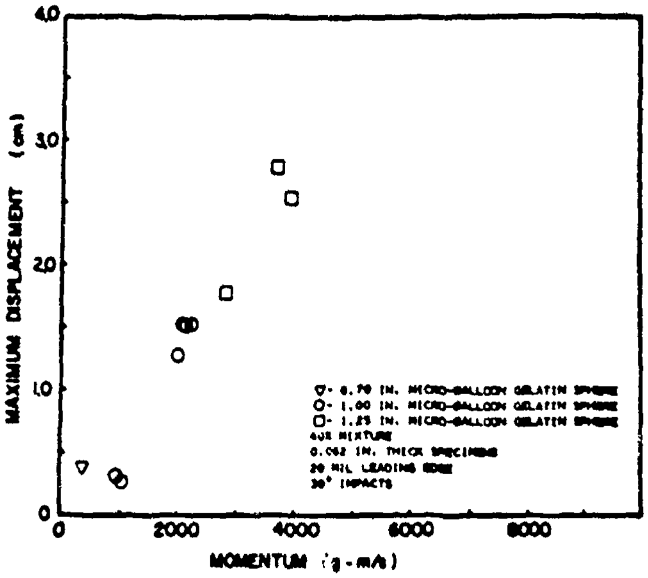

Figure 22. Plot of maximum displacement versus momentum for 40 percent microballoon gelatin.

TABLE 1
SUMMATION OF IMPACTS ON TAPERED TITANIUM BLADES USING 40% MICROBALLOON GELATIN PROJECTILES

SPECIMEN SIZE (W x L x T) (cm)	MOUNTING TYPE	PROJECTILE TYPE	PROJECTILE SIZE (cm)	IMPACT VELOCITY (m/s)	PLASTIC DEFORMATION (cm³)	FRONTAL AREA (cm²)	MAXIMUM DISPLACEMENT (cm)
[illegible] (1)	Fixed-Fixed	40% Microballoon Gelatin	1.78	[illegible]	[illegible]	[illegible]	0.30
[illegible] (2)	Fixed-Fixed	"	2.54	319.0	[illegible]	[illegible]	[illegible]
[illegible] (5)	Fixed-Fixed Cantilever Free-Free	"	2.54	[illegible]	[illegible]	[illegible]	[illegible]
[illegible] (1)	Fixed-Fixed	"	3.18	[illegible]	[illegible]	[illegible]	1.78
[illegible] (2)	Fixed-Fixed	"	3.18	[illegible]	[illegible]	[illegible]	[illegible]

NOTE: Number in parenthesis indicates number of tests conducted in that group.

similar test conditions are grouped together and averaged. The number in parenthesis in the table indicates the number of tests at similar test conditions (impactor type, size, and velocity) in that group.

3.2.2 15 Percent Microballoon-Gelatin Projectile

The second series of thirty-one tests utilized tapered-edge specimens with projectiles made from a mixture of 15 percent microballoons in gelatin. The blade parameters investigated in this series of tests included the size of the specimens (width and length), the specimen thickness, and the leading-edge thickness. The impact parameters investigated included the projectile size and the angle of incidence.

The two specimen sizes used in the tests were 7.62 x 22.86 cm and 7.62 x 31.75 cm (width and length). Two specimen thicknesses investigated were the nominally 0.16 cm and 0.32 cm values. The leading-edge thickness of the specimens was either 0.051 cm or 0.102 cm with the taper angle of four degrees.

The projectiles were spheres of a mixture of 15 percent microballoon in gelatin with diameters of 1.27, 2.54, and 3.18 cm. Three methods of specimen mounting were used including the fixed-fixed, the cantilever, and the free-free techniques. The impact angle was either 15 or 30 degrees.

For the first five leading-edge impact tests using the 15 percent microballoon-gelatin projectiles, values of the projectile mass impacting the targets were not measureable using the previously developed ballistic felt backstop technique. The non-impact portion of the 15 percent microballoon-gelatin projectiles were broken into many small pieces upon impact. The 40 percent microballoon-gelatin projectile non-impact slices were not broken up and were easily recoverable from the ballistic felt. This problem was solved by using a cardboard box filled with ballistic felt to trap the non-impact projectile particles. The cardboard box was weighed before and after each impact and the mass of the non-impact portion of the projectile determined. The mass of the projectile impact on the target was then calculated from the initial sphere mass and the trapped non-impact portion mass.

The projectile impact velocity of the thirty-one tests ranged from a low of 284 m/s to a high of 516 m/s. The impact velocity for the majority of the testing was approximately 475 m/s.

Plots of the measured damage values versus the impact momentum are given in Figures 23 through 25. Figure 23 gives a plot of the measured plastic deformation area damage while Figure 24 and 25 show plots of the frontal area damage and maximum deformation damage measurements, respectively.

A summary of the damage results for the tapered specimens and the 15 percent microballoon-gelatin projectiles is given in Table 2. Impacts at similar test conditions are grouped together and averaged. The number in parenthesis in the table indicates the number of tests (impactor type, size, and velocity) in that group.

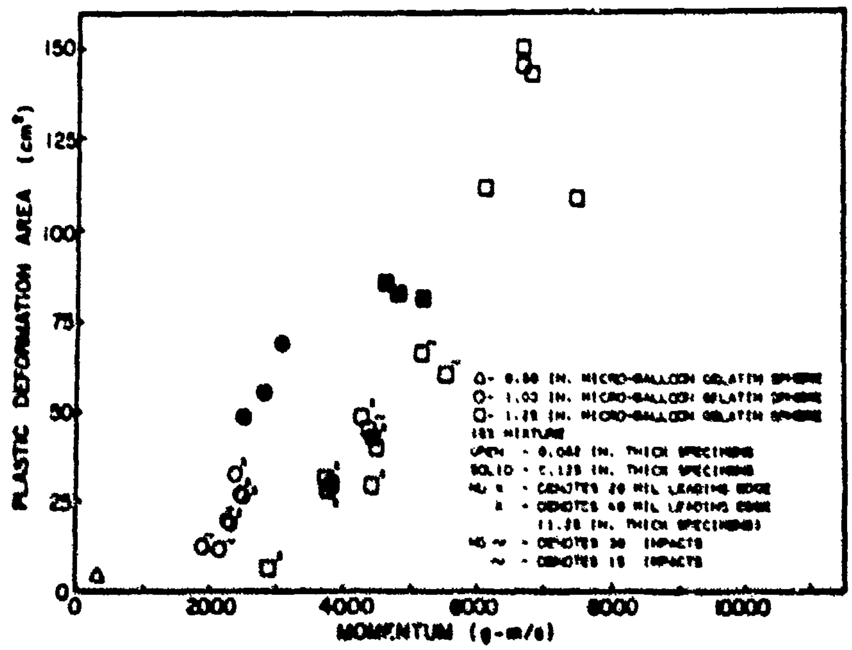

Figure 23. Plot of plastic deformation area versus momentum for 15 percent microballoon-gelatin.

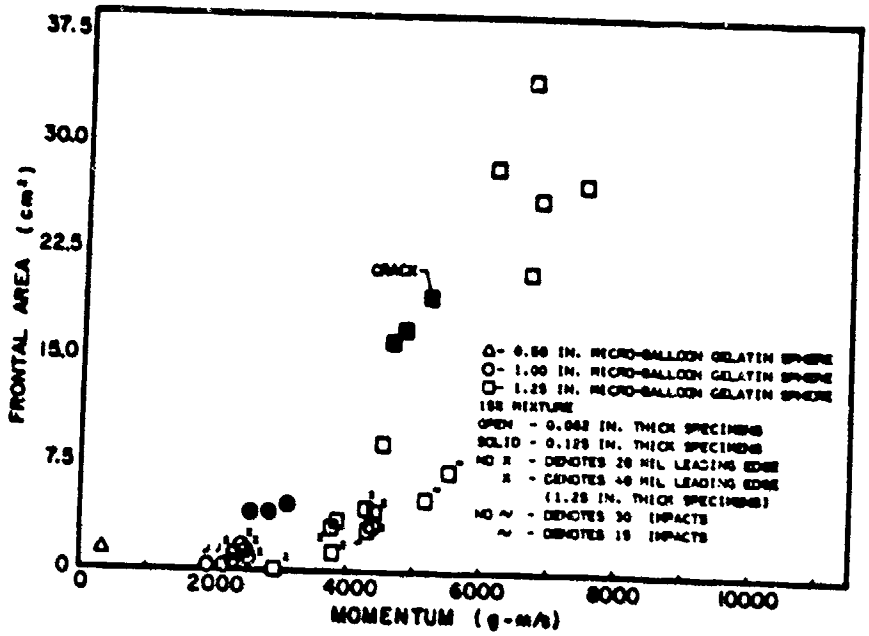

Figure 24. Plot of frontal area versus momentum for 15 percent micro-balloon-gelatin.

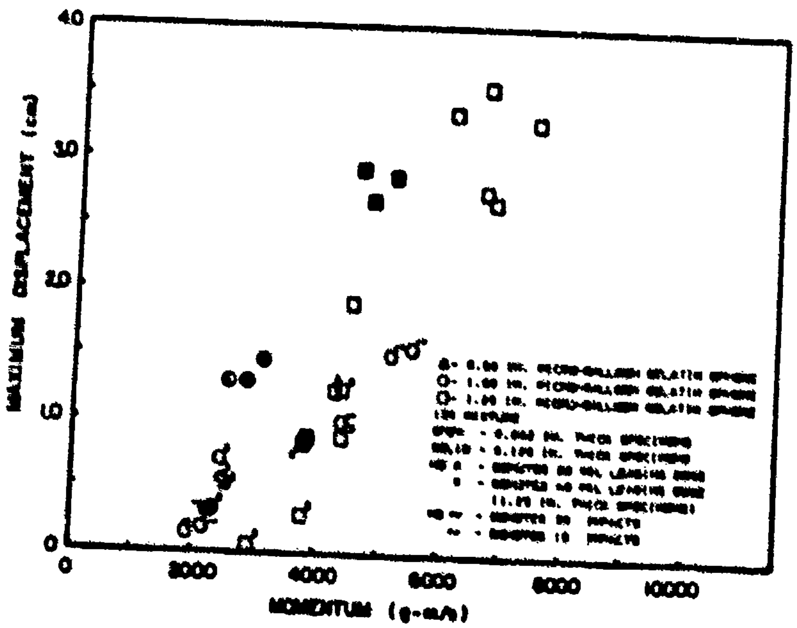

Figure 25. Plot of maximum displacement versus momentum for 15 percent microballoon-gelatin.

TABLE 2

SUMMATION OF IMPACTS ON TAPERED TITANIUM BLADES USING 15% MICROBALLOON GELATIN PROJECTILES

SPECIMEN SIZE (WxLxT) (cm)	SPECIMEN LEADING EDGE THICKNESS (cm)	MOUNTING TYPE	PROJECTILE TYPE	PROJECTILE SIZE (cm)	IMPACT VELOCITY (m/s)	IMPACT ANGLE (°)	PLASTIC DEFORMATION AREA (cm²)	FRONTAL AREA (cm²)	MAXIMUM DISPLACEMENT (cm)	MAXIMUM STRAIN (%)
7.62x31.75x0.16 (1)	0.051	Fixed-Fixed	15% Microballoon Gelatin	1.27	497.2	30°	4.19	1.29	0.13	-
7.62x31.75x0.16 (3)	0.051	Fixed-Fixed Cantilever Free-Free	"	2.54	466.0	15°	14.39	0.37	0.22	-
7.62x31.75x0.16 (3)	0.051	Fixed-Fixed Cantilever Free-Free	"	3.18	468.7	15°	56.75	4.97	1.35	-
7.62x31.75x0.16 (1)	0.051	Cantilever	"	3.18	292.3	30°	29.48	3.61	0.85	-
7.62x31.75x0.16 (1)	0.051	Cantilever	"	3.18	359.1	30°	39.61	0.84	1.91	-
7.62x27.86x0.16 (3) 7.62x31.75x0.16 (3)	0.051	Fixed-Fixed Cantilever Free-Free	"	3.18	482.7	30°	131.78	27.35	3.13	28
7.62x27.86x0.32 (3)	0.051	Fixed-Fixed Cantilever Free-Free	"	2.54	479.1	30°	57.51	4.24	1.33	13
7.62x27.86x0.32 (3)	0.051	Fixed-Fixed Cantilever Free-Free	"	3.18	476.6	30°	83.05	17.33	2.82	32
7.62x31.75x0.32 (4)	0.102	Fixed-Fixed Cantilever Free-Free	"	2.54	482.4	30°	26.16	1.31	0.53	-
7.62x31.75x0.32 (1)	0.102	Fixed-Fixed	"	3.18	284.1	30°	6.65	0.12	0.05	-
7.62x31.75x0.32 (1)	0.102	Fixed-Fixed	"	3.18	371.9	30°	28.71	1.29	0.30	-
7.62x31.75x0.32 (1)	0.102	Fixed-Fixed	"	3.18	422.8	[illegible]	30.19	3.10	0.84	-
7.62x31.75x0.32 (3)	0.102	Fixed-Fixed Cantilever Free-Free	"	3.18	471.5	30°	40.06	3.89	1.13	-

Note: Number in parenthesis indicates number of tests conducted in that group.

3.3 EFFECT OF VARIOUS PARAMETERS ON SPECIMEN DAMAGE

Important projectile, impact, and geometry parameters were varied in the testing to determine the effect of the various parameters on the specimen damage. In most instances, only several impacts were conducted for a particular parameter at defined impact conditions to obtain an insight on the sensitivity of the particular parameter on specimen damage. No attempt was conducted to determine the scaling laws of the various parameters on the specimen damage because of insufficient data; however, the trend or direction of the damage (greater or less) was established for the various parameters.

The following paragraphs discuss the trend of the specimen damage for the various parameters varied.

3.3.1 Projectile Parameters

The two projectile parameters investigated in the testing are projectile density and projectile size.

3.3.1.1 Effect of Projectile Density on Damage

The density of the microballoon-gelatin projectile material showed little effect on the plastic deformation area and maximum displacement damage; however, a substantial effect resulted in the frontal area measurement for 3.18 cm sphere impacts at similar test conditions as shown in the damage results of Table 3. The higher density (15 percent) microballoon-gelatin generates about 17 percent more damage in the plastic deformation area, 17 percent more damage for the maximum displacement, and a 70 percent damage increase for the frontal area measurement than for the 40 percent microballoon gelatin mixture. The effect of projectile density is shown in Figure 26.

3.3.1.2 Effect of Projectile Size on Damage

The effect of projectile size in regard to inflicting damage is distinctly shown in Table 4 and Figures 20 through 22 for 40 percent microballoon-gelatin projectiles. For similar impact conditions, the plastic deformation and frontal area measurements for the 2.54 cm sphere impacts are about ten times that for the 1.78 cm sphere impacts. The maximum displacement for the larger sphere impacts is about 3.8 times that for the smaller sphere. Increasing the projectile diameter size to 3.18 cm from 2.54 cm increased the plastic deformation area about twice, the frontal area damage about 3.6 times, and the maximum displacement damage about 1.8 times. Typical damage for the various size 40 percent microballoon-gelatin projectiles is shown in Figure 27.

TABLE 3
DAMAGE RESULTS FOR COMPARING EFFECT OF PROJECTILE DENSITY

SPECIMEN SIZE (WxLxT) (cm)	SPECIMEN LEADING EDGE THICKNESS (cm)	MOUNTING TYPE	PROJECTILE TYPE	PROJECTILE SIZE (cm)	IMPACT VELOCITY (m/s)	IMPACT ANGLE (°)	PLASTIC DEFORMATION AREA (cm²)	FRONTAL AREA (cm²)	MAXIMUM DISPLACEMENT (cm)	MAXIMUM STRAIN (%)
7.62x22.86x0.13 (1) 10.16x30.48x0.16 (1)	0.051	Fixed-Fixed	40% Microballoon Gelatin	3.18	477.4	30°	112.45	16.05	2.67	-----
7.62x27.86x0.16 (2) 7.62x31.75x0.16 (3)	0.051	Fixed-Fixed Cantilever Free-Free	15% Microballoon Gelatin	3.18	482.7	30°	131.78	27.35	3.13	20

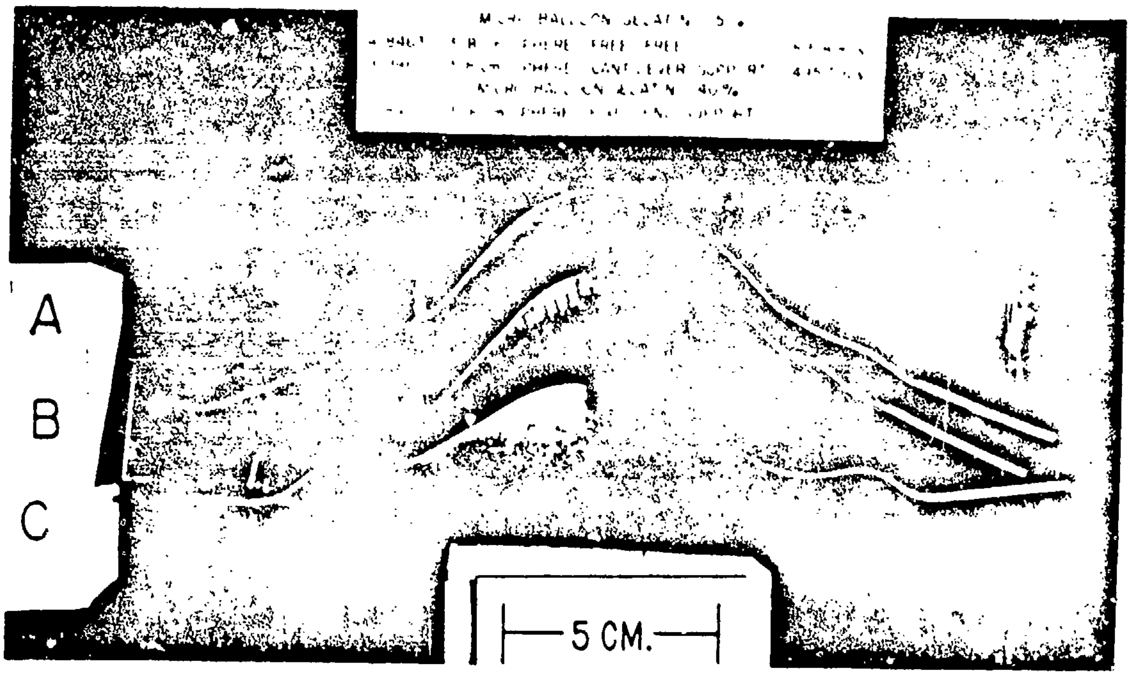

Figure 26. Effect of projectile density on damage.

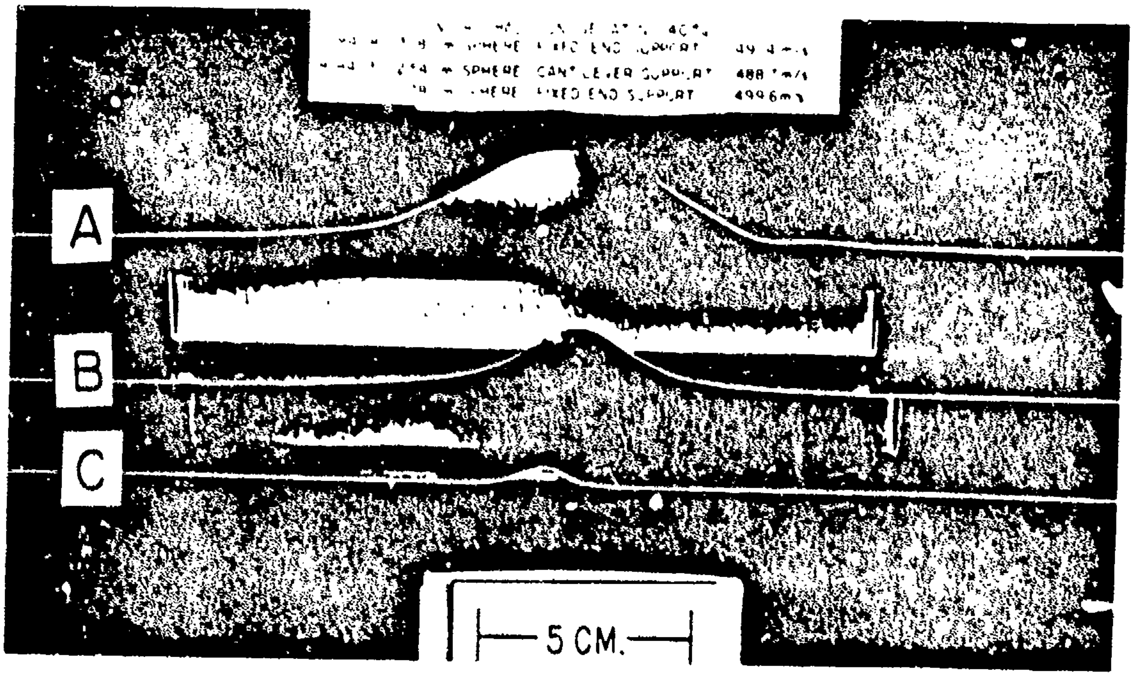

Figure 27. Effect of projectile size on damage.

The effect of projectile size on damage for 15 percent micro-balloon gelatin projectiles is also shown in Table 4 for 15 degree incidence angle impacts. For similar impact conditions, the plastic deformation area damage for 3.18 cm spheres is about four times that for 2.54 cm impacts. The frontal area and maximum displacement damage for 3.18 cm impacts is about 13 times and six times that for 2.54 cm impacts, respectively. Thus, an increase in projectile size will substantially increase specimen damage.

3.3.2 Impact Parameters

Two impact parameters investigated in the testing are impact velocity and angle of incidence.

3.3.2.1 Effect of Impact Velocity on Damage

It was determined from the testing that local damage is very sensitive to impact velocity. The effect of impact velocity is shown in Table 5 for micro-balloon gelatin projectile impacts. The table shows the average damage for 3.18 cm diameter sphere impacts on 0.051 cm thick leading-edges at an incidence angle of 30 degrees. The results show that increasing the impact velocity will substantially increase all damage measurements. It was demonstrated in the Phase 1 testing that all area measurements of the damage increase with increasing impact velocity until perforation occurs. Upon perforation, the damage decreases with increasing velocity.

3.3.2.2 Effect of Incidence Angle on Damage

It was determined from the testing that local damage is very sensitive to incidence angle. The effect of incidence angle is shown in Table 6. The table shows the average damage of three or more tests (fixed-fixed, cantilever, and free-free methods of mounting) for 2.54 cm and 3.18 cm spheres of 15 percent microballoon gelatin on 0.051 cm thick leading-edges. The average impact velocities are very similar (about 470 m/s). All the 15 degree incidence angle impacts and the 3.18 cm sphere impacts at an incidence angle of 30 degrees were conducted on 0.16 cm thick specimens whereas the 2.54 cm sphere impacts at 30 degrees incidence angle were conducted on 0.32 cm thick specimens. The table shows that the damage for the 2.54 cm impacts at 30 degrees on the thicker specimens is similar to that for the 3.18 cm impacts at 15 degree incidence angles on the thinner targets. The results indicate that decreasing the incidence angle greatly reduces the damage.

TABLE 4

DAMAGE RESULTS FOR COMPARING EFFECT OF PROJECTILE SIZE

SPECIMEN SIZE (WxLxT) (cm)	SPECIMEN LEADING EDGE THICKNESS (cm)	MOUNTING TYPE	PROJECTILE TYPE	PROJECTILE SIZE (cm)	IMPACT VELOCITY (m/s)	IMPACT ANGLE (°)	PLASTIC DEFORMATION AREA (cm^2)	FRONTAL AREA (cm^2)	MAXIMUM DISPLACEMENT (cm)
7.62x22.86x0.16 (5) 10.16x33.10x0.16	0.051	Fixed-Fixed Cantilever Free-Free	40% Microballoon Gelatin	2.54	489.8	30~	63.29	4.52	1.47
7.62x22.86x0.16 (2) 10.16x38.10x0.16	0.051	Fixed-Fixed	"	3.18	477.4	30°	112.45	16.06	2.67
7.62x31.75x0.16 (3)	0.051	Fixed-Fixed Cantilever Free-Free	15% Microballoon Gelatin	2.54	466.0	15°	14.39	0.37	0.22
7.62x31.75x0.16 (3)	0.051	Fixed-Fixed Cantilever Free-Free	"	3.18	468.7	15°	56.75	4.97	1.35

TABLE 5

DAMAGE RESULTS FOR COMPARING EFFECT OF IMPACT VELOCITY

SPECIMEN SIZE (WxLxT) (cm)	SPECIMEN LEADING EDGE THICKNESS (cm)	MOUNTING TYPE	PROJECTILE TYPE	PROJECTILE SIZE (cm)	IMPACT VELOCITY (m/s)	IMPACT ANGLE (°)	PLASTIC DEFORMATION AREA (cm^2)	FRONTAL AREA (cm^2)	MAXIMUM DISPLACEMENT (cm)	MAXIMUM STRAIN (%)
7.62x31.75x0.16 (1)	0.051	Cantilever	15% Microballoon Gelatin	3.18	292.3	30°	29.48	3.61	0.89	-----
7.62x31.75x0.16 (1)	0.051	Cantilever	"	3.18	359.1	30°	39.61	8.84	1.91	-----
7.62x22.86x0.16 (2) 7.62x31.75x0.16 (3)	0.051	Fixed-Fixed Cantilever Free-Free	"	3.18	482.7	30°	131.78	27.35	3.13	28

TABLE 6
MEASURED LOCAL DAMAGE FOR 15° and 30° IMPACTS
ON 0.051 cm THICK LEADING-EDGE SPECIMENS

SPECIMEN THICKNESS (cm)	PROJECTILE SIZE (cm)	IMPACT VELOCITY (m/s)	IMPACT ANGLE (°)	PLASTIC DEFORMATION AREA (cm^2)	FRONTAL AREA (cm)	MAXIMUM DISPLACEMENT (cm)
0.16	2.54	466.0	15°	14.39	0.37	0.22
0.16	3.18	468.7	15°	56.75	4.97	1.35
0.32	2.54	479.1	30°	57.51	4.24	1.33
0.16	3.18	482.7	30°	131.78	27.35	3.13

3.3.3 Specimen Parameters

The specimen parameters investigated in the testing include specimen shape, size, mounting, overall thickness, and leading-edge thickness.

3.3.3.1 Effect of Specimen Shape on Damage

It was established in the testing that typical damage generated on flat (constant thickness) specimens does not resemble that of an actual blade as shown in Figure 1. It was necessary to utilize specimens with a tapered edge to generate damage similar to that received by actual fan blades.

3.3.3.2 Effect of Specimen Size on Damage

The effect of specimen size (width and length values) showed negligible influence on the 2.54 cm diameter sphere impacts and some differences in the damage for the larger 3.18 cm diameter projectiles. On the 7.62 x 22.86 x 0.16 cm specimens, extra ripples in the leading edge away from the impact site were received for 3.18 cm sphere impacts. This indicated that the specimen size may be too small for the 3.18 cm projectile impact and boundary effects were important. These extra ripples in the

leading edge are shown in Figure 28. Increasing the specimen size to 7.62 x 31.75 x 0.16 cm in the second series of testing eliminated the extra ripples; however, increasing the specimen length resulted in a greater specimen bending at the mounting fixtures. Table 7 shows gives results of for the two specimen sizes. Notice that the greatest difference is in the length dimension of the plastic deformation area damage.

3.3.3.3 Effect of Boundary Conditions on Damage

The effect of different boundary conditions (fixed-fixed, cantilever, and free-free methods of mounting) was negligible in regard to damage received. The damage measurement results were very similar for the three methods of mounting. This indicates that the damage is generated in very short times and occurs during the impact event. Table 8 shows typical damage that was received for the three methods of specimen mounting. Typical damage for the three methods of specimen mounting are shown in Figure 29.

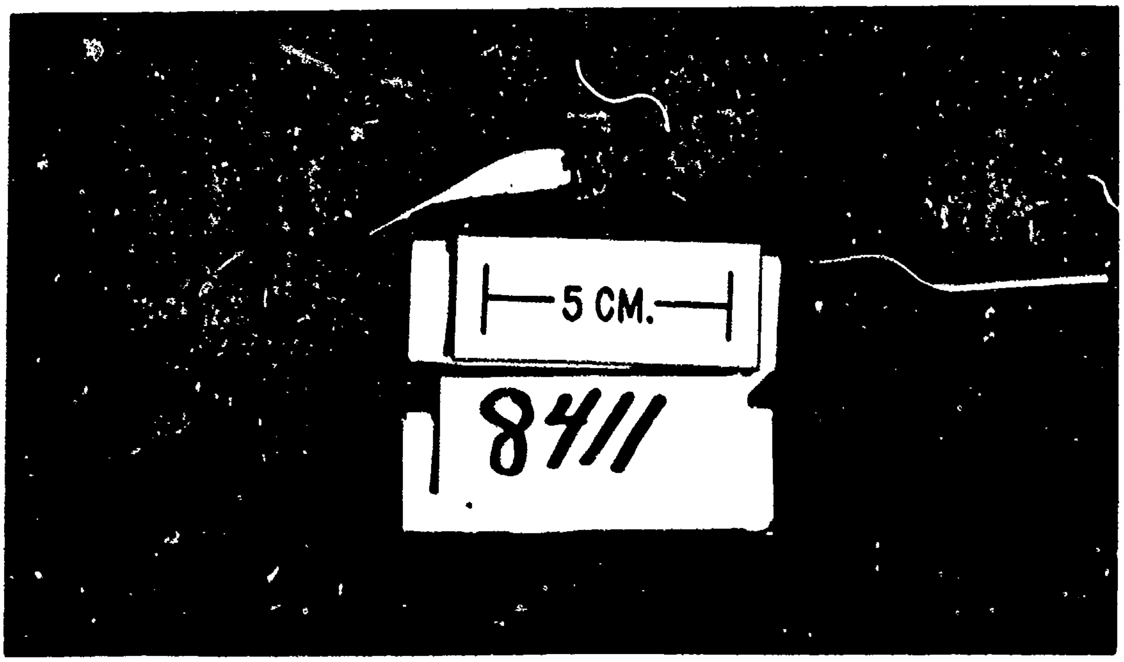

Figure 28. Effect of specimen size on damage.

TABLE 7
DAMAGE RESULTS FOR COMPARING EFFECT OF SPECIMEN SIZE

SHOT	TARGET MATERIAL	TARGET SIZE/SHAPE (WxLxT) (cm)	TAPER ANGLE (°)	LEADING EDGE THICKNESS AT IMPACT SITE (cm)	SUPPORT METHOD	PROJECTILE SIZE (cm)	PROJECTILE TYPE	IMPACT VELOCITY (m/s)	IMPACT ANGLE (°)	PLASTIC DEFORMATION AREA (cm²) [LxW(cm)]	FRONTAL AREA (cm²)	MAXIMUM DISPLACEMENT (cm)	IMPACT MASS (Kg)	STRAIN DEGREE INITIAL (cm)	STRAIN DEGREE POST IMPACT (cm)
0462	Ti 6-4	7.62x22.86 x0.17 Tapered	4°	0.05	Cantilever	3.18	158 "	495.7	0	111.94 [17.02 6.86]	28.26	3.35	-	0.25	0.33
0463	Ti 6-4	7.62x22.86 x0.17 Tapered	4°	0.05	Free-Free	3.18	"	515.8	0	108.71 [16.51 6.86]	27.10	3.30	-	15.24	17.78
0464	Ti 6-4	7.62x31.75 x0.17 Tapered	4°	0.05	Fixed-Fixed	3.18	"	461.2	0	149.87 [24.89 6.35]	34.26	3.56	-	0.64	0.81
0465	Ti 6-4	7.62x31.75 x0.17 Tapered	4°	0.05	Cantilever	3.18	"	472.5	0	143.10 [24.64 6.29]	26.18	2.67	-	0.64	0.79
0466	Ti 6-4	7.62x31.75 x0.17 Tapered	4°	0.05	Free-Free	3.18	"	468.2	0	145.16 [24.13 6.73]	20.97	2.79	-	0.64	0.84

TABLE 8
DAMAGE RESULTS FOR COMPARING
THREE METHODS OF MOUNTING

SHOT	TARGET MATERIAL	TARGET SIZE/SHAPE (WxLxT) (cm)	TAPER ANGLE (°)	LEADING EDGE THICKNESS AT IMPACT SITE (cm)	SUPPORT METHOD	PROJECTILE SIZE (cm)	PROJECTILE TYPE	IMPACT VELOCITY (m/s)	IMPACT ANGLE (°)	PLASTIC DEFORMATION AREA (cm²) [LxW(cm)]	FRONTAL AREA (cm²)	MAXIMUM DISPLACEMENT (cm)	IMPACT MASS (Kg)	STRAIN DEGREE INITIAL (cm)	STRAIN DEGREE POST IMPACT (cm)
0462	Ti 6-4	10.16x38.1 x0.17 Tapered	4°	0.05	Fixed-Fixed	2.54	40% Microballoon Gelatin	524.6	30°	67.19 [14.22 5.46]	5.16	1.52	.00401	15.24	15.35
0463	Ti 6-4	10.16x38.1 x0.17 Tapered	4°	0.05	Cantilever	"	"	488.7	"	52.13 [14.35 4.83]	4.45	1.27	.00409	"	15.57
0465	Ti 6-4	7.62x22.86 x0.17 Tapered	4°	0.05	Fixed-Fixed	"	"	459.7	"	67.87 [16.00 4.67	4.45	1.52	.00450	"	15.80
0466	Ti 6-4	7.62x22.86 x0.17 Tapered	4°	0.05	Cantilever	"	"	471.3	"	61.61 [14.38 5.00]	4.06	1.52	.00439	"	15.00
0467	Ti 6-4	7.62x22.86 x0.17 Tapered	4°	0.05	Free-Free	"	"	504.5	"	72.77 [16.30 5.59]	4.45	1.52	.00439	"	15.75
0470	Ti 6-4	7.62x22.86 x0.32 Tapered	4°	0.05	Fixed-Fixed	3.18	15% Micro-balloon Gelatin	470.6		81.03 [15.49 5.59]	10.23	2.87	.01484	0.84	0.86
0471	Ti 6-4	7.62x22.86 x0.32 Tapered	4°	0.05	Free-Free	3.18	"	477.7	"	82.64 [15.88 5.33	16.77	2.67	.01005	0.84	0.86

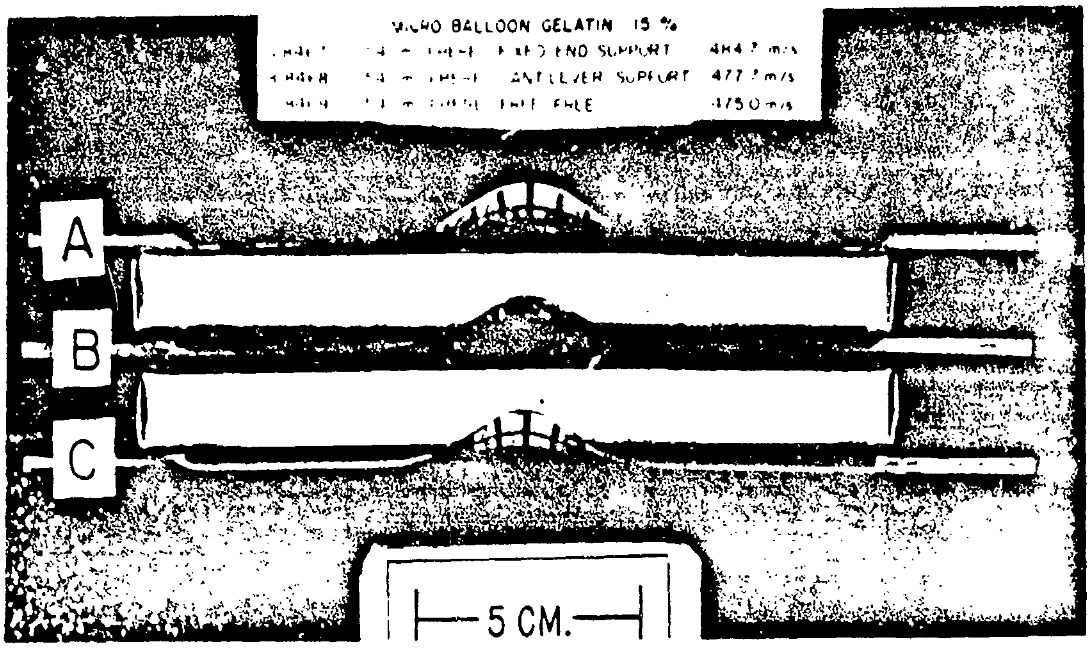

Figure 29. Effect of method of specimen mounting on damage.

3.3.3.4 Effect of Specimen Thickness on Damage

The effect of specimen thickness can be demonstrated by considering the 3.18 cm diameter 15 percent microballoon-gelatin projectiles for 30 degree impacts. Table 9 shows the average results for the 3.18 cm diameter projectile impacts. Increasing the specimen thickness from 0.16 cm to 0.32 cm without changing the leading-edge thickness of 0.051 cm decreased the amount of damage. The plastic deformation area damage decreased about 40 percent, the frontal area damage decreased about 37 percent and the maximum displacement damage decreased about ten percent. One advantage of using the thicker specimens was that a great deal of the specimen structural bending was reduced. Typical damage on the thicker specimens utilizing the three methods of target mounting is shown in Figure 30.

3.3.3.5 Effect of Leading-Edge Thickness on Damage

The effect of doubling the leading-edge thickness (0.051 cm to 0.102 cm) decreased the local damage about the same amount for both 2.54 cm and 3.18 cm impacts on 0.32 cm thick specimens. The damage for the 0.051 cm leading-edge impacts by 2.54 cm projectiles was 2.2 times greater for the plastic deformation area than for the 0.102 cm leading-edge specimens. The frontal area and maximum displacement for the thinner leading-edge was 3.2

TABLE 9. DAMAGE RESULTS FOR COMPARING EFFECT OF SPECIMEN THICKNESS

SPECIMEN SIZE (WxLxT) (cm)	SPECIMEN LEADING EDGE THICKNESS (cm)	MOUNTING TYPE	PROJECTILE TYPE	PROJECTILE SIZE (cm)	IMPACT VELOCITY (m/s)	IMPACT ANGLE	PLASTIC DEFORMATION AREA (cm^2)	FRONTAL AREA (cm^2)	MAXIMUM DISPLACEMENT (cm)	MAXIMUM STRAIN (%)
7.62x22.86x0.16 (2) 7.62x31.75x0.16 (3)	0.051	Fixed-Fixed Cantilever Free-Free	15% Microballoon Gelatin	3.18	482.7	30°	131.78	27.35	3.13	78
7.62x22.86x0.32 (3)	0.051	Fixed-Fixed Cantilever Free-Free	"	3.18	476.6	30°	83.05	17.33	2.82	32

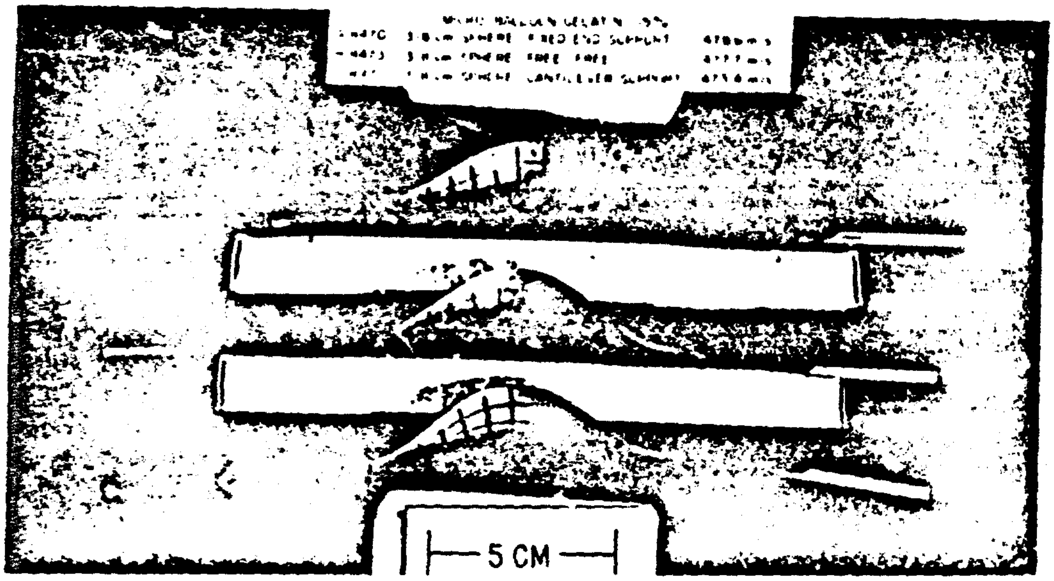

Figure 30. Typical damage on thicker specimens utilizing three methods of mounting.

and [illegible] times greater, respectively, than for the thicker leading-edge targets for the 2.54 cm impacts. For the 3.18 cm projectile impacts, the plastic deformation area damage for the thinner leading-edge was 2.1 times greater than for the thicker leading-edge impacts. Similarly, the frontal area and maximum displacement damage of the 3.18 cm impacts was 4.5 and 2.5 times greater for impacts on the thinner leading-edge targets. Table 10 gives the damage results for comparing the effect of doubling the leading edge thickness.

3.4 STRAIN MEASUREMENTS OF LEADING EDGES

A measure of the strain on the leading-edges at the impact site was determined by painting a grid on selected specimens. By making post-impact measurements of the grid, the strain for a 0.63 cm grid was about 30 percent for the 3.18 cm sphere impacts and 13 percent for the 2.54 cm spheres for impact velocities of approximately 480 m/s. In all of the Phase 2 testing, only one impact (Shot #8470) generated a crack at the impact site of the leading-edge. This crack had a length of 2.03 cm for the 3.18 cm sphere impact at a velocity of 470 m/s and an incidence angle of 30 degrees. The

TABLE 10. DAMAGE RESULTS FOR COMPARING THE EFFECT OF INCREASING THE LEADING EDGE THICKNESS

SPECIMEN SIZE (WxLxT) (cm)	SPECIMEN LEADING EDGE THICKNESS (cm)	MOUNTING TYPE	PROJECTILE TYPE	PROJECTILE SIZE (cm)	IMPACT VELOCITY (m/s)	IMPACT ANGLE (°)	PLASTIC DEFORMATION AREA (cm^2)	FRONTAL AREA (cm^2)	MAXIMUM DISPLACEMENT (cm)	MAXIMUM STRAIN (%)
7.62x22.86x0.32[3]	0.051	Fixed-Fixed Cantilever Free-Free	15% Microballoon Gelatin	2.54	479.1	30°	57.51	4.24	1.33	13
7.62x31.75x0.32[4]	0.102	Fixed-Fixed Cantilever Free-Free	"	2.54	482.4	30°	26.16	1.31	0.53	--
7.62x22.86x0.32[3]	0.051	Fixed-Fixed Cantilever Free-Free	"	3.18	476.6	30°	83.05	17.33	2.82	32
7.62x31.75x0.32[3]	0.102	Fixed-Fixed Cantilever Free-Free	"	3.18	471.5	30°	40.06	3.89	1.13	--

target for this impact had a leading-edge thickness of 0.051 cm and the target size was 7.62 x 22.86 x 0.32 cm (width, length, and thickness dimensions). Figure 31 shows a photograph of the specimen with the crack.

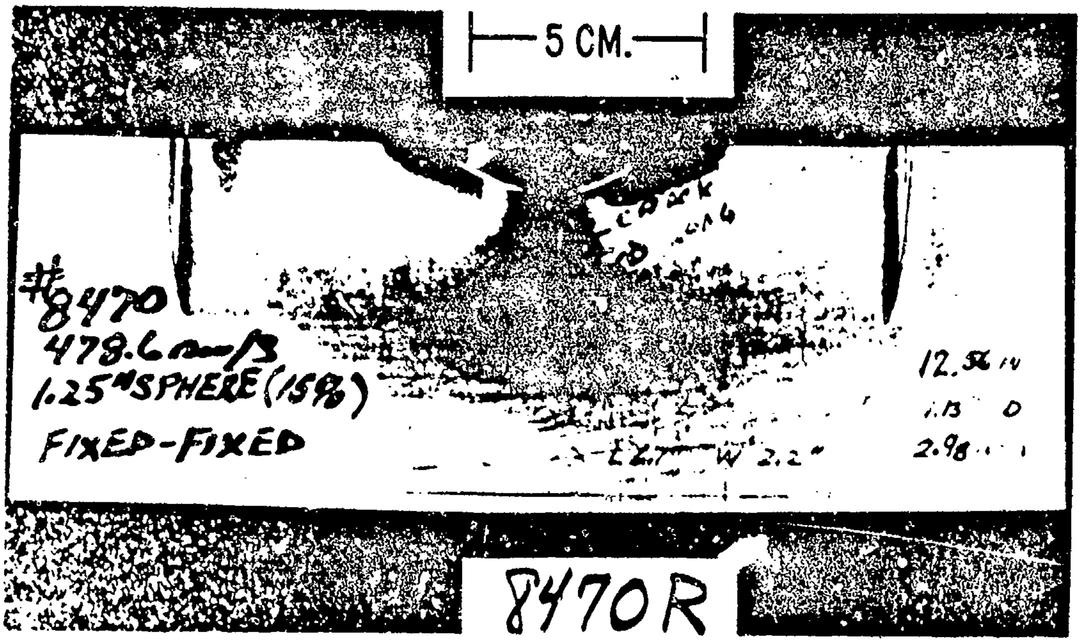

Figure 31. Photograph showing crack damage on specimen.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

A number of general conclusions may be drawn from the data generated in this study. The local damage problem to aircraft engine fan blades was investigated by conducting leading-edge soft-body impacts on flat-edge and tapered-edge laboratory size titanium specimens. The conclusions for the various parameters investigated in the study are as follows:

1. Specimen Shape

It has been demonstrated in this study that the local damage generated on laboratory size titanium specimens by leading-edge impacts, by substitute birds, can duplicate that received from an actual titanium blade from a birdstrike; however, the laboratory specimens require a tapered-edge similar to the geometry of actual blades. Thus, the local damage is very sensitive to blade geometry.

2. Impact Velocity

In the study, separate distinct damage modes were identified on the tapered-edge specimens. Plastic deformation occurs at the lower velocities, cracking and metal roll-back at higher velocities, and finally, cracking with metal roll-back and penetration (metal missing) at the highest velocities.

It was determined from the Phase 1 testing that the momentum transfer to the target and all damage area measurements increase in value with increasing impact velocity until specimen penetration occurs. Upon penetration, they decrease in value.

3. Boundary Conditions

The effect of different boundary conditions (fixed-fixed, cantilever, and free-free methods of mounting) was negligible in regard to damage received. Similar damage measurements were recorded for all three methods of mounting. This indicates that the damage is generated in very short times and occurs during the impact event.

4. Specimen Size

The effect of specimen size (width and length values) showed negligible influence on damage received for 2.54 cm sphere impacts and some differences in the damage for the 3.18 cm sphere projectiles. On the 7.62 x 22.86 x 0.16 cm specimens, extra ripples occurred in the leading edge away from the impact site for 3.18 cm projectile impacts. This indicated that the specimen size may have been too small for the 3.18 cm impacts. Increasing the specimen size to 7.62 x 31.75 x 0.16 cm eliminated the extra ripples; however, increasing the specimen length resulted in greater specimen bending.

5. Projectile Size

The effect of projectile size in regard to inflicting damage was determined to be substantial. For the lower density projectile impacts, the plastic deformation and frontal area damage for 2.54 cm spheres are about 10 times that for 1.78 cm spheres while the maximum displacement increased only 3.8 times as much. Increasing the projectile size to 3.18 cm spheres increased the plastic deformation area and maximum displacement about two times that for 2.54 cm spheres and the frontal area about 3.6 times.

For the higher density projectiles, the effect of projectile size to generate damage was again substantial. For similar impact conditions, the plastic deformation area damage for 3.18 cm spheres was about four times that for 2.54 cm impacts. The frontal area and maximum displacement damage for 3.18 cm impacts was about 13 times and 6 times that for 2.54 cm impacts, respectively.

6. Projectile Density

The effect of density of the projectile material showed little influence on the plastic deformation and maximum displacement damage; however, a substantial effect resulted in the frontal area measurement. The higher density projectile material impacts generated 17 percent more damage for the plastic deformation area and maximum displacement and 70 percent more damage for the frontal area measurement than for the lower density microballoon gelatin mixture.

7. Specimen Thickness

The effect of specimen thickness showed considerable influence on the damage. Increasing the specimen thickness from 0.16 cm to 0.32 cm without charging the leading-edge thickness decreased the amount of damage. The plastic deformation area decreased about 40 percent while the frontal area

damage decreased about 37 percent. The maximum displacement damage decreased only about 10 percent for the thicker specimens. One advantage of the thicker specimens was that specimen bending was reduced substantially.

8. Incidence Angle

It was determined from the testing that local damage is very sensitive to incidence angle. An increase in the incidence angle substantially increased the damage. The damage for 2.54 cm impacts at 30 degrees on the thicker specimens (0.32 cm) was very similar to that for 3.18 cm impacts at 15 degree incidence angles on the thinner targets.

9. Specimen Leading-Edge Thickness

The effect of doubling the leading-edge thickness decreased the local damage about the same amount for both 2.54 cm and 3.18 cm impacts on 0.32 cm thick specimens. The damage for the thinner leading-edge impacts by 2.54 cm projectiles was 2.2 times greater for the plastic deformation area than for the thicker leading-edge. The frontal area and maximum displacement for the thinner leading-edge was 3.2 and 2.5 times greater, respectively, than for the thicker leading-edge targets for 2.54 cm impacts. In regards to 3.18 cm projectile impacts, the plastic deformation area damage for the thinner leading-edge was 2.1 times greater, the frontal area 4.1 times greater, and the maximum displacement 2.5 times greater than for the thicker leading-edge specimens.

10. Strain Measurements

The measured strain for a 0.63 cm grid on the leading-edge at the impact site was about 30 percent for the 3.18 cm sphere impacts and 13 percent for the 2.54 cm spheres at impact velocities of approximately 480 m/s.

4.2 RECOMMENDATIONS

Additional testing would be required to fully understand the complex ballistic response of specimens for soft-body leading-edge impacts. Emphasis should be placed upon the following recommendations:

1. Additional testing on titanium specimens is needed to determine the scaling laws governing the various projectile, impact, and specimen parameters important on generating local damage.

2. A testing program using aluminum and steel alloy specimens is needed to determine material properties most sensitive to impact damage.

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APPENDIX A

PHASE 1 TEST RESULTS

SHOT	TARGET MATERIAL	TARGET SIZE/SHAPE (LxWxT) (cm)	TAPER ANGLE (°)	LEADING EDGE THICKNESS (cm)	SUPPORT METHOD	PROJECTILE SIZE/TYPE (cm)		IMPACT VELOCITY (m/s)	IMPACT ANGLE (°)	IMPACT MASS (Kg)	MEASURED MOMENTUM TRANSFER (N-S)	CALCULATED MOMENTUM (N-S)	REMARKS
8208	6AL-4VTI	7.62x22.86 x0.17 Flat	-	-	Fixed-Fixed	2.54	RTV560	272	90	0.9086	0.9086	-	Slight deformation. Plastic deformation area = 13.35 cm^2
8209	"	"	-	-	"	"	"	366	"	Broke-up	1.2819	-	Slight deformation. Plastic deformation area = 53.94 cm^2. Frontal area = 1.03^2cm .
8210	"	"	-	-	"	"	"	211	"	0.00356	0.5449	-	No visual damage. No deformation. Frontal area = 0.00 cm^2.
8211	"	"	-	-	"	"	"	59	"	Remained Intact	0.3182	-	No visual damage. No deformation. Frontal area = 0.00 cm^2.
8212	"	"	-	-	"	"	"	996	"	Broke-up	1.4718	-	Large deformation. Plastic deformation area = 67.74 cm^2. Frontal area = 3.03 cm^2.
8213	"	7.62x22.86 x0.10 Flat	-	-	"	"	"	445	"	0.00354	0.9581	-	Large deformation. Plastic area = 106.77 cm^2. Frontal area = 5.16 cm^2.
8214	Ti-75	7.62x22.86 x0.05 Flat	-	-	"	"	"	454	"	0.00395	0.6572	-	Specimen split at both ends at clamps. Frontal area = 25.03 cm^2.
8215	"	"	-	-	"	"	"	456	"	0.00335	0.8403	-	Specimen split at both ends. Frontal area = 19.35 cm^2.
8216	"	"	-	-	"	"	"	445	30	0.00098	0.531	-	Specimen split and broke at clamps. Frontal area = 19.35 cm^2.
8217	6AL-4VTI	7.62x22.86 x0.10 Flat	-	-	"	"	"	450	"	0.00151	1.1895	-	Specimen broke on one end. Frontal area = 5.61 cm^2. Plastic area = 81.35 cm^2.
8218	Ti-75	7.62x22.86 x0.05 Flat	-	-	"	"	"	433	"	0.00131	1.5849	-	Specimen broke at clamps and impacted pendulum. Frontal area = 13.42^2cm .
8219	"	"	-	-	"	"	Pure Gelatin	439	"	0.00365	1.1306	-	Specimen broke at clamps into free section. Frontal area = 11.23 cm^2.

SHOT	TARGET MATERIAL	TARGET SIZE/SHAPE (LxWxT) (cm)	TAPER ANGLE (°)	LEADING EDGE THICKNESS (cm)	SUPPORT METHOD	PROJECTILE SIZE/TYPE (cm)		IMPACT VELOCITY (m/s)	IMPACT ANGLE (°)	IMPACT MASS (Kg)	MEASURED MOMENTUM TRANSFER (N-S)	CALCULATED MOMENTUM (N-S)	REMARKS
8220	Ti-75	7.62x22.86† x0.05 Flat	-	-	Fixed-Fixed	2.54	RTV560	431	30	0.00157	1.6438	-	Extreme damage to specimen. Frontal area = 11.35 cm^2.
8221	6-4 Ti	7.62x22.86 x0.21	4.6	0.03	"	"	"	418	"	Broke-up. Maximum Displacement = 1.78 cm	1.283	-	Splitting and roll-back at impact site. Plastic area = 59.23 cm^2. Frontal area = 8.77 cm^2.
8222	"	"	4.0	0.05	"	"	"	310	"	0.00272 Maximum Displacement = 0.46 cm	No Picture	-	Moderate deformation. Plastic area = 10.52 cm^2. Frontal area = 0.71 cm^2. $\frac{mv^2}{2}$ = 149 joules
8223	"	"	4.2	0.04	"	"	"	220	"	0.00208 Maximum Displacement = 0.08 cm	0.4839	-	Slight deformation. Plastic area = [illegible] cm^2. Frontal area = 0.06 cm^2. $\frac{mv^2}{2}$ = 91 joules
8224	"	"	4.5	0.03	"	"	"	360 (est)	"	0.00201 Maximum Displacement = 1.32 cm	1.0756	-	Large deformation. Plastic area = 55.94 cm^2. Frontal area = 6.06 cm^2. $\frac{mv^2}{2}$ = 231 joules
8225	"	"	4.7	0.02	"	"	"	456	"	0.00168 Maximum Displacement = 1.57 cm	1.0535	-	Roll-back and metal missing at impact site. Plastic area = 34.52 cm^2. Frontal area = 3.10 cm^2. $\frac{mv^2}{2}$ = 499 joules
8226	AL	7.82x22.86 x6.80 Flat	-	-	"	"	"	202	"	0.0028	0.301	0.141	Calibration shots on thick AL with impact edge rounded to give a sharp edge.

† Sandwiched between two 5.08x22.86x0.10 Ti on each side.

SHOT	TARGET MATERIAL	TARGET SIZE/SHAPE (LxWxT) (cm)	TAPER ANGLE (°)	LEADING EDGE THICKNESS (cm)	SUPPORT METHOD	PROJECTILE SIZE/TYPE (cm)	IMPACT VELOCITY (m/s)	IMPACT ANGLE (°)	IMPACT MASS (Kg)	MEASURED MOMENTUM TRANSFER (N-S)	CALCULATED MOMENTUM (N-S)	REMARKS
8228	AL	7.62x22.86 x0.80 Flat	-	-	Fixed-fixed	2.54 RTV560	310	30	0.00263	0.358	0.204	
8229	"	"	-	-	"	" "	311	"	0.00283	0.347	0.220	Debris impact angle = 33.8°
8230	"	"	-	-	"	" "	310	90	0.00646	2.032	2.003	Pendulum calibration
8231	"	"	-	-	"	" "	400	"	0.00657	2.703	2.628	Pendulum calibration. Projectile trapped in tube mounted within pendulum.
8232	"	"	-	-	"	" "	228	"	0.00651	1.495	1.484	" " "
8233	"	"	-	-	"	" "	310	30	0.00256	0.313	0.235*	Debris angle off plate = 36°. ϕ = 36° - 30° = 6°. Target rounded impact edge sharpened to prevent free slice of projectile to deflect at angle.
8234	"	"	-	-	"	" "	316	"	0.00265	0.324	0.240*	Debris angle = 34.8°. Target same as 8233.
8235	"	"	-	-	"	" "	306	"	0.00242	0.280	0.211*	Debris angle = 34.6. Target same as 8233.
8236	"	"	-	-	"	" "	402	"	0.00417	0.816	0.494*	Target deformed. Debris angle = 35.9°. Plastic area = 2.77 cm^2. Frontal area = 0.52 cm^2.
8237	"	"	-	-	"	" "	210	"	0.00250	0.235	0.160*	Debris angle = 37.2°
8238	"	"	-	-	"	" Pure Gelatin	288	"	Broke-up	0.626	-	Debris angle = 36.0°
8239	"	"	-	-	"	" "	175	"	0.00362	0.235	0.183*	Debris angle = 35.2°
8240	"	"	-	-	"	" RTV560	253	"	0.00388	0.391	0.391†	Debris (impact) Angle = 35° Debris (no impact) angle = 6° Residual velocity = 229 m/s Cutting momentum = 0.059 N/S(3.7%)

*Calculated using measured debris angle (mv sin 30° + mv cos 30° tan ϕ) sin 30°

†Includes cutting momentum

SHOT	TARGET MATERIAL	TARGET SIZE/SHAPE (LxWxT) (cm)	TAPER ANGLE (°)	LEADING EDGE THICKNESS (cm)	SUPPORT METHOD	PROJECTILE SIZE/SHAPE (cm)		IMPACT VELOCITY (m/s)	IMPACT ANGLE (°)	IMPACT MASS (Kg)	MEASURED MOMENTUM TRANSFER (N-S)	CALCULATED MOMENTUM (N-S)	REMARKS
8241	AL	7.62x22.86 x0.60 Flat	-	-	Fixed-Fixed	2.54	RTV560	308	30	0.00300	0.358	0.332†	Debris (impact) angle = 35.2° Debris (no impact) angle = 2.8° Residual velocity = 289 m/s Cutting momentum = 0.064 N/S(3.3%)
8242	"	"	-	-	"	"	"	295	"	0.00292	0.346	0.303†	Debris (impact) angle = 35.2° Debris (no impact) angle = 2.7° Residual velocity = 280 m/s Cutting momentum - 0.053 N/S(2.8%)
8243	"	"	-	-	"	"	"	430	"	0.00107	0.190	0.184†	Debris (impact) angle = 36.1° Debris (no impact) angle = 3.8° Residual velocity = 387 m/s Cutting momentum = 0.047 N/S(5%)
8244	"	"	-	-	"	"	"	425	"	0.00216	0.31215	0.2658	Debris angle = 35.2°
8245	6-4 Ti	7.62x22.86	0	.04	"	"	"	425	"	0.00051	0.4847	-	Moderate deformation. Plastic area = 11.48 cm². Frontal area = 1.81 cm². Maximum plastic deformation = 0.71 cm.
8246	"	"	3.7	.04	"	"	"	501	"	0.00199	0.5510	-	Moderate deformation. Plastic area = 20.06 cm². Frontal area = 2.06 cm². Debris angle = 39.5° Maximum plastic deformation = = 0.91 cm.
8247	"	"	3.8	.04	"	"	"	547	"	0.00112	0.4077	-	Moderate deformation. Plastic area = 13.55 cm . Frontal area = 2.13 cm . Maximum plastic deformation = 0.94 cm. Debris angle = 40.7°.
8248	"	"	3.7	.04	"	"	"	607	"	0.000729	0.5291	-	Splitting and roll-back at impact site. Plastic area = 26.90 cm². Frontal area = 3.74 cm². Debris angle = 44.0°. Maximum deformation = 1.14 cm.

† Includes cutting momentum

SHOT	TARGET MATERIAL	TARGET SIZE/SHAPE (LxWxT) (cm)	TAPER ANGLE (°)	LEADING EDGE THICKNESS (cm)	SUPPORT METHOD	PROJECTILE SIZE/SHAPE (cm)	IMPACT VELOCITY (m/s)	IMPACT ANGLE (°)	IMPACT MASS (Kg)	MEASURED MOMENTUM TRANSFER (N-S)	CALCULATED MOMENTUM (N-S)	REMARKS
8249	6-4 Ti	7.62x22.86 x0.21 Taper	3.7	.04	Fixed-Fixed	2.54 RTV560	688	30	Broke-up	0.463	-	Some plastic deformation to specimen. Projectile broke-up on launch and only slight damage resulted.
8250	"	"	3.7	.04	"	" "	434	"	0.00157	1.356	-	Large deformation. Plastic area = 62.65 cm^2. Frontal area = 7.94 cm^2. Debris angle = 50.2. Maximum plastic deformation = 1.52 cm.

APPENDIX B

PHASE 2 TEST RESULTS

SHOT	TARGET MATERIAL	TARGET SIZE/SHAPE (WxLxT) (cm)	TAPER ANGLE (°)	LEADING EDGE THICKNESS AT IMPACT SITE (cm)	SUPPORT METHOD	PROJECTILE SIZE (cm)	PROJECTILE TYPE	IMPACT VELOCITY (m/s)	IMPACT ANGLE (°)	PLASTIC DEFORMATION AREA (cm^2) [LxW(cm)]	FRONTAL AREA (cm^2)	MAXIMUM DISPLACEMENT (cm)	IMPACT MASS (Kg)	STRAIN DEGREE INITIAL (cm)	STRAIN DEGREE POST IMPACT (cm)
0397	Ti 3-4	10.16x30.1 x0.17 Flat	None	0.17	Fixed-Fixed	2.54	40% Micro-Balloon Gelatin	141.7	30°	-	-	-	.00333	-	-
0398	Ti 6-4	10.16x30.1 x0.17 Flat	None	0.17	Fixed-Fixed	"	"	303.4	"	-	-	-	.00360	-	-
0399	Ti 6-4	10.16x30.1 x0.17 Flat	None	0.17	Fixed-Fixed	"	"	477.1	"	29.74 [9.19 4.17]	1.10	0.30	.00446	15.24	15.39
0400	Ti 6-4	10.16x30.1 x0.17 Flat	None	0.17	Cantilever	"	"	477.1	"	16.77 [6.45 3.43]	0.15	0.13	.00332	"	15.32
0441	Ti 6-4	10.16x30.1 x0.17 Tapered	4°	0.05	Fixed-Fixed	"	"	310.9	"	13.29 [5.33 3.18]	0.39	0.25	.00330	"	15.37
0442	Ti 6-4	10.16x30.1 x0.17 Tapered	4°	0.05	Fixed-Fixed	"	"	524.6	"	62.19 [14.22 5.46]	5.16	1.52	.00401	"	15.85
0443	Ti 6-4	10.16x30.1 x0.17 Tapered	4°	0.05	Cantilever	"	"	488.7	"	52.13 [14.35 4.83]	4.45	1.27	.00409	"	15.57
0444	Ti 6-4	7.62x22.86 x0.17 Tapered	4°	0.05	Fixed-Fixed	"	"	317.0	"	8.00 [2.84 3.30]	0.39	0.30	.00297	"	15.37
0445	Ti 6-4	7.62x22.86 x0.17 Tapered	4°	0.05	Fixed-Fixed	"	"	459.7	"	67.87 [16.09 4.37]	4.45	1.52	.00450	"	15.80
0446	Ti 6-4	7.62x22.86 x0.17 Tapered	4°	0.05	Cantilever	"	"	471.3	"	[illegible]1.61 [14.38 5.08]	4.06	1.52	.00439	"	15.46
0447	Ti 6-4	7.62x22.86 x0.17 Tapered	4°	0.05	Free-Free	"	"	504.5	"	72.77 [16.00 5.59]	4.45	1.52	.00439	"	15.75
0448	Ti 6-4	10.16x30.1 x0.17 Tapered	4°	0.05	Fixed-Fixed	8.10	"	491.4	"	111.81 [19.05 7.24]	13.68	2.54	.00803	"	16.38

SHOT	TARGET MATERIAL	TARGET SIZE/SHAPE (WxLxT) (cm)	TAPER ANGLE (°)	LEADING EDGE THICKNESS AT IMPACT SITE (cm)	SUPPORT METHOD	PROJECTILE SIZE (cm)	PROJECTILE TYPE	IMPACT VELOCITY (m/s)	IMPACT ANGLE (°)	PLASTIC DEFORMATION AREA (cm²) [LxW(cm)]	FRONTAL AREA (cm²)	MAXIMUM DISPLACEMENT (cm)	IMPACT MASS (Kg)	STRAIN DEGREE INITIAL (cm)	STRAIN DEGREE POST IMPACT (cm)
0409	Ti 6-4	10.16x38.1 x0.17 Tapered	6°	0.05	Fixed-Fixed	3.18	40% Micro-Balloon Gelatin	389.0	30°	104.90 [18.42 7.11]	8.32	1.78	.00720	15.24	15.80
0410	Ti 6-4	10.16x38.1 x0.17 Tapered	6°	0.05	=	1.78	=	499.6	=	6.26 [3.94 2.16]	0.45	0.38	.00069	15.24	15.37
0411	Ti 6-4	7.62x22.86 x0.17 Tapered	6°	0.05	=	3.18	=	462.4	=	113.03 [16.26 6.6]	18.45	2.79	.00797	15.24	17.02
0442	Ti 6-4	7.62x22.86 x0.17 Tapered	[illegible]	0.05	Cantilever	3.18	15% =	495.7	=	111.94 [17.02 6.86]	20.26	3.35	-	0.25	0.33
0443	Ti 6-4	7.62x22.86 x0.17 Tapered	6°	0.05	Free-Free	3.18	=	515.8	=	108.71 [16.51 6.86]	27.10	3.30	-	15.24	17.78
0444	Ti 6-4	7.62x31.75 x0.17 Tapered	6°	0.05	Fixed-Fixed	3.18	=	461.2	=	149.07 [24.89 6.35]	34.26	3.56	-	0.64	0.81
0445	Ti 6-4	7.62x31.75 x0.17 Tapered	6°	0.05	Cantilever	3.18	=	472.5	=	143.10 [24.64 6.29]	26.19	2.67	-	0.64	0.79
0446	Ti 6-4	7.62x31.75 x0.17 Tapered	6°	0.05	Free-Free	3.18	=	468.2	=	145.16 [24.13 6.73]	20.97	2.79	-	0.64	0.84
0467	Ti 6-4	7.62x22.86 x0.32 Tapered	6°	0.05	Fixed-Fixed	2.54	=	484.7	=	68.90 [15.49 5.46]	4.65	1.45	.00635	0.64	0.71
0468	Ti 6-4	7.62x22.86 x0.32 Tapered	6°	0.05	Cantilever	2.54	=	477.7	=	55.23 [14.99 5.08]	4.06	1.27	.00595	0.64	0.71
0469	Ti 6-4	7.62x22.86 x0.32 Tapered	6°	0.05	Free-Free	2.54	=	475.0	=	48.39 [13.21 4.95]	4.00	1.27	.00536	0.64	0.74
0470	Ti 6-4	7.62x22.86 x0.32 Tapered	6°	0.05	Fixed-Fixed	3.18	=	478.6	=	81.03 [15.49 5.59]	19.23	2.87	.01084	0.64	0.86
0471	Ti 6-4	7.62x22.86 x0.32 Tapered	6°	0.05	Cantilever	3.18	=	473.4	=	85.48 [16.00 5.59]	15.00	2.92	.00981	0.64	0.81

SHOT	TARGET MATERIAL	TARGET SIZE/SHAPE (WxLxT) (cm)	TAPER ANGLE (°)	LEADING EDGE THICKNESS AT IMPACT SITE (cm)	SUPPORT METHOD	PROJECTILE SIZE (cm)	PROJECTILE TYPE	IMPACT VELOCITY (m/s)	IMPACT ANGLE (°)	PLASTIC DEFORMATION AREA (cm²) [LxW(cm)]	FRONTAL AREA (cm²)	MAXIMUM DISPLACEMENT (cm)	IMPACT MASS (Kg)	STRAIN DEGREE INITIAL (cm)	STRAIN DEGREE POST IMPACT (cm)
8473	Ti 6-4	7.62x22.86 x0.32 Tapered	4°	0.05	Free-Free	3.18	15% Micro-balloon Gelatin	477.7	30°	82.04 [15.88 5.33]	16.77	2.67	.01005	0.04	0.04
8548	Ti 6-4	7.62x31.75 x0.32 Tapered	4°	0.10	Fixed-Fixed	2.54	"	484.7	"	32.58 [8.08 4.90]	1.74	0.71	.00500 (est)	-	-
8549	Ti 6-4	7.62x31.75 x0.32 Tapered	4°	0.10	Fixed-Fixed	2.54	"	482.3	"	26.84 [7.37 4.62]	1.48	0.56	.00515	-	-
8550	Ti 6-4	7.62x31.75 x0.32 Tapered	4°	0.10	Cantilever	2.54	"	475.2	"	26.45 [7.19 4.37]	0.97	0.51	.00526	-	-
8551	Ti 6-4	7.62x31.75 x0.32 Tapered	4°	0.10	Free-Free	2.54	"	483.5	"	18.77 [6.78 3.81]	1.03	0.33	.00485	-	-
8552	Ti 6-4	7.62x31.75 x0.16 Tapered	4°	0.05	Fixed-Fixed	1.27	"	494.2	"	4.19 [3.07 1.93]	1.29	0.13	.00070	-	-
8553	Ti 6-4	7.62x31.75 x0.16 Tapered	4°	0.05	Fixed-Fixed	1.27	"	497.2	"	4.19 [3.07 1.93]	1.29	0.13	.00070	-	-
8554	Ti 6-4	7.62x31.75 x0.32 Tapered	4°	0.10	Free-Free	3.18	"	461.8	"	42.39 [9.60 5.03]	3.10	0.89	.00957	-	-
8555	Ti 6-4	7.62x31.75 x0.32 Tapered	4°	0.10	Fixed-Fixed	3.18	"	475.6	"	48.19 [10.97 5.8]	4.39	1.24	.009001	-	-
8556	Ti 6-4	7.62x31.75 x0.32 Tapered	4°	0.10	Cantilever	3.18	"	477.1	"	29.61 [9.35 4.75]	4.19	1.24	.00931	-	-
8557	Ti 6-4	7.62x31.75 x0.32 Tapered	4°	0.10	Fixed-Fixed	3.18	"	204.1	"	6.65 [4.88 2.16]	0.12	0.05	.01027	-	-
8558	Ti 6-4	7.62x31.75 x0.32 Tapered	4°	0.10	Fixed-Fixed	3.18	"	371.0	"	28.71 [8.38 4.34]	1.29	0.30	.01022	-	-
8559	Ti 6-4	7.62x31.75 x0.32 Tapered	4°	0.10	Fixed-Fixed	3.18	"	472.6	"	30.19 [9.56 4.83]	3.10	0.84	.00899	-	-

SHOT	TARGET MATERIAL	TARGET SIZE/SHAPE (WxLxT) (cm)	TAPER ANGLE (°)	LEADING EDGE THICKNESS AT IMPACT SITE (cm)	SUPPORT METHOD	PROJECTILE SIZE (cm)	PROJECTILE TYPE	IMPACT VELOCITY (m/s)	IMPACT ANGLE (°)	PLASTIC DEFORMATION AREA (cm^2) [LxW(cm)]	FRONTAL AREA (cm^2)	MAXIMUM DISPLACEMENT (cm)	IMPACT MASS (Kg)	STRAIN DEGREE INITIAL (cm)	STRAIN DEGREE POST IMPACT (cm)
8560	Ti 6-4	7.62x31.75 x0.16 Tapered	4°	0.05	Fixed-Fixed	3.18	15% Micro-Balloon Gelatin	468.9	15°	60.06 [11.94 5.69]	6.91	1.57	.01181	-	-
8561	Ti 6-4	7.62x31.75 x0.16 Tapered	4°	0.05	Cantilever	3.18	"	460.9	"	44.26 [8.32 5.49]	1.17	0.99	.00953	-	-
8562	Ti 6-4	7.62x31.75 x0.16 Tapered	4°	0.05	Free-Free	3.18	"	476.2	"	65.94 [13.31 6.02]	5.03	1.50	.01089	-	-
8563	Ti 6-4	7.62x31.75 x0.16 Tapered	4°	0.05	Fixed-Fixed	2.54	"	469.5	"	19.03 [5.97 3.63]	0.52	0.33	.00493	-	-
8564	Ti 6-4	7.62x31.75 x0.16 Tapered	4°	0.05	Free-Free	2.54	"	464.0	"	11.81 [3.94 3.05]	0.32	0.18	.00467	-	-
8565	Ti 6-4	7.62x31.75 x0.16 Tapered	4°	0.05	Cantilever	2.54	"	464.6	"	12.32 [4.57 3.02]	0.26	0.15	.00411	-	-
8566	Ti 6-4	7.62x31.75 x0.16 Tapered	4°	0.05	Cantilever	3.18	"	292.3	30°	29.48 [9.30 5.08]	3.61	0.85	.013205	-	-
8567	Ti 6-4	7.62x31.75 x0.16 Tapered	4°	0.05	Cantilever	3.18	"	359.1	"	39.61 [10.62 5.59]	8.04	1.91	.012565	-	-

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